Berger · Berghold · Brugger · Burtscher
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Mountain and High-Altitude Medicine

ÖSTER. GESELLSCHAFT FÜR ALPIN- UND HÖHENMEDIZIN

BExMed

Springer

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Marc Moritz Berger • Franz Berghold
Hermann Brugger • Martin Burtscher
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Editors

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Preface to the Third Edition

Dear readers,

We are very pleased that you are now holding the third edition of *Mountain and High-Altitude Medicine* in your hands. Prof. Dr. Franz Berghold, the founder of the Mountain Doctors' Courses in Austria, initiated this work. The first edition was published in 2015, followed by the second edition in 2019. In the meantime, the book *Mountain and Altitude Medicine* has become established as a reference work. For example, it serves as the theoretical foundation for medical training in the Mountain Doctors' Courses in Austria and as the study material for the examination leading to the internationally recognized Diploma in Mountain Medicine (DIMM). The Mountain Doctors' Courses, founded and DIMM-accredited by Prof. Dr. Franz Berghold, are by far the most widely attended courses of their kind worldwide.

Sadly, Prof. Dr. Franz Berghold passed away in spring 2023 after a long and serious illness. With Prof. Dr. Franz Berghold, we have lost a highly esteemed friend and a tireless promoter of Mountain and High-Altitude Medicine in the German-speaking world. Prof. Dr. Franz Berghold deserves great thanks for initiating and editing this work.

Two further editors, Prof. Dr. Wolfgang Domej and Dr. Wolfgang Schaffert, have stepped down due to age; our gratitude also goes to them. We are pleased to welcome the renowned high-altitude medicine expert Prof. Dr. Marc Moritz Berger as a new editor. We extend a warm welcome to him as part of our editorial team.

The third edition of *Mountain and High-Altitude Medicine* has undergone significant development. Most chapters have been thoroughly revised. In addition, many chapters have been completely rewritten due to a generational change among several authors. For example, the new chapter "Physiology of Moderate, High and Extreme Altitudes" (▶ Chap. 4) summarizes all relevant changes in body functions at altitude. The substantially expanded new chapter "Mountaineering and Hiking with Pre-existing Conditions" (▶ Chap. 21) provides a comprehensive discussion of internal, neurological, and psychiatric diseases. New chapters also include "Suspension Syndrome" (▶ Chap. 33), "Alpine Polytrauma," and "Pulse Oximetry" (▶ Chap. 10). The book concludes with another new chapter, "New Technologies in Mountain and High-Altitude Medicine" (▶ Chap. 47).

We wish you much enjoyment as you browse and discover.

Spring 2024

For the English version of this book, we are glad to welcome Dr. Jonathan White and Dr. John Ellerton as English language editors. We would like to thank them very much for the valuable work.

PS: Constructive feedback on *Mountain and High-Altitude Medicine* is very welcome: peter.paal@icloud.com.

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History of Alpine Medicine

Walter Phleps, Franz Berghold, and Gerhard Flora

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1.1 Origins of Mountain Medicine

1.1.1 Humans and the Alps

For millennia, the earliest human response to the mountains was sheer fear, a raw terror of the dreadful spirits and cruel demons believed to lurk behind the howling storms and thundering avalanches. Dante, the greatest poet of the Middle Ages, fittingly placed hell on a mountain in his *Divine Comedy*, for there, "terror is heaped upon terror, and the abysses roar their horror at each other". In any case, humans had no place there.

The Alps formed an almost insurmountable barrier between the major cultural regions of Europe. One of the few historically documented crossings of the Alps was that of the military commander Hannibal, who in 218 BC led around 50,000 men, 9000 cavalry, and 37 war elephants across the southern Alps, enduring unimaginable hardship and heavy losses. Nevertheless, many Alpine passes had been frequented by travellers and trade caravans since ancient times, even though, according to legend, dragons and sinister beings lurked there, dragging some brave wanderers to their doom.

It was not until the Renaissance that nature enthusiasts and botanists broke the spell that had until then closed off the mountains. In the second half of the eighteenth century, the Age of Enlightenment ushered in a new era in the relationship between humans and the mountains. It was scholars who first ascended the highest Alpine peaks—physicists and geologists, geographers and glaciologists. Nobles and humanists were also courageous pioneers of alpinism. Alongside scientific interests, the ideas of Romanticism are unmistakable, especially the call of Jean-Jacques Rousseau (1712–1778): "Retournons à la nature!" This "return to nature" was supplemented later by "up into the mountains!" Accordingly, in August 1786, the first footsteps were taken on the summit of the highest peak in the Alps, the 4810 m Mont Blanc. Other peaks followed: the Kleinglockner in 1799 and the Großglockner (3798 m; ◘ Fig. 1.1) in 1800.

By the mid-nineteenth century, mountaineering had gradually become a mass movement. The first alpine associations were founded to open up the mountains and make them accessible to the general public: the Austrian Alpine Club in 1862 and the German Alpine Club in 1869. Today, these two associations are considered the largest alpine organisations in the Alps.

History of Alpine Rescue Services

- 1896 to 1938: Founding era
- 1942 to 1960: Era of the development of alpine rescue equipment
- 1960 to present: Era of alpine air rescue
- 1980 to present: Era of electronic aids

1.1.2 Beginnings of Alpine Rescue, Founding Era

From around the twelfth century, hostels had been established on the high Alpine passes for pilgrims, travellers, trade caravans, and other wayfarers. In 1386, Heinrich Findelkind founded the hospice at the Arlberg Pass, whose brotherhood searched for lost persons and provided other Samaritan services. The avalanche rescue dogs of the Great St Bernard Pass became legendary, their deployment in all weather conditions gaining worldwide fame, not least because of the supposedly life-saving barrels of rum hanging from their collars (◘ Fig. 1.2).

The increasing number of ascents in the second half of the nineteenth century inevitably led to serious accidents. At that time, the recovery of casualties was left entirely to their climbing partners, who had neither technical rescue training nor suitable transport equipment. Remote mountain farmers faced similar challenges—thus, the first carrying frames were developed in the mountains (◘ Figs. 1.3 and 1.4).

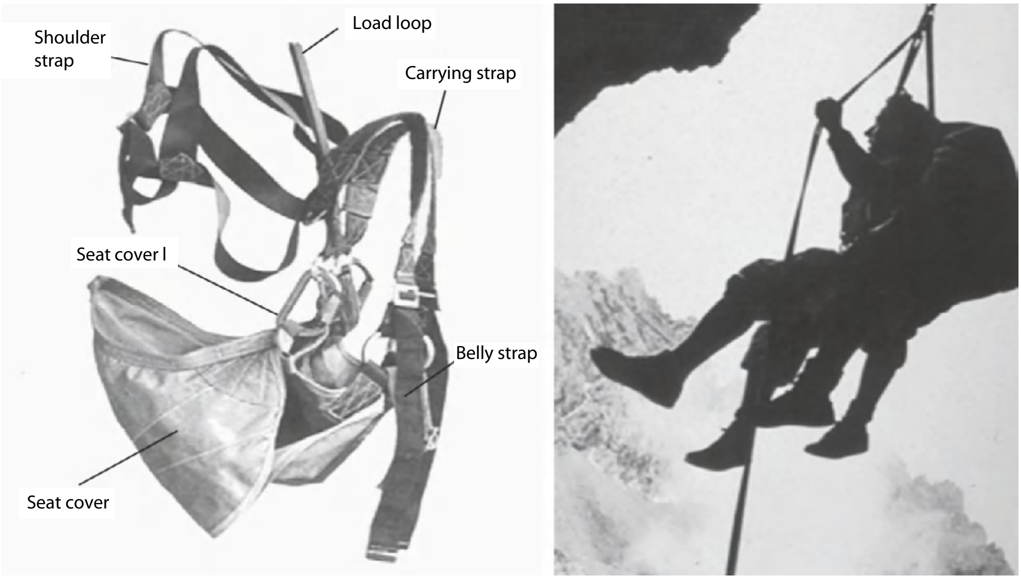

Shoulder strap
Load loop
Carrying strap
Seat cover I
Belly strap
Seat cover

Fig. 1.1 Markus Pernhart (1824–1871): Großglockner from the Hohewart Saddle, oil on canvas. (Carinthia State Museum, Klagenfurt)

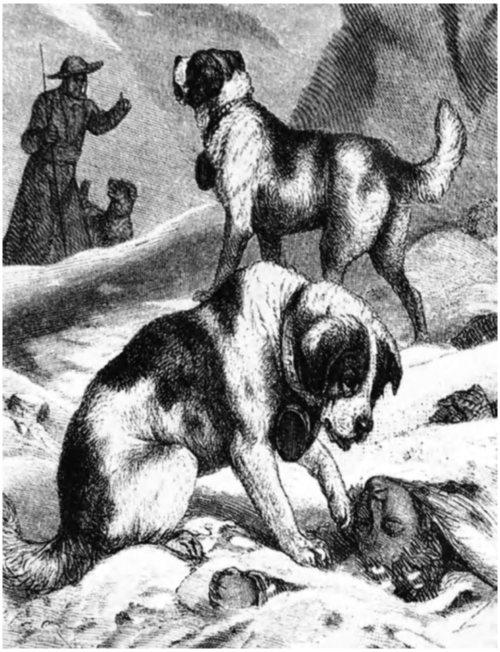


Fig. 1.2 Avalanche rescue dog operation at the Great St Bernard Pass

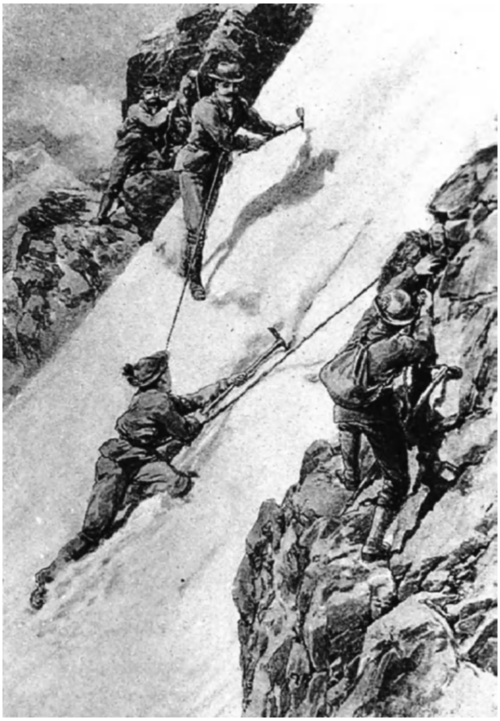


Fig. 1.3 Minor mountain accident, circa 1880

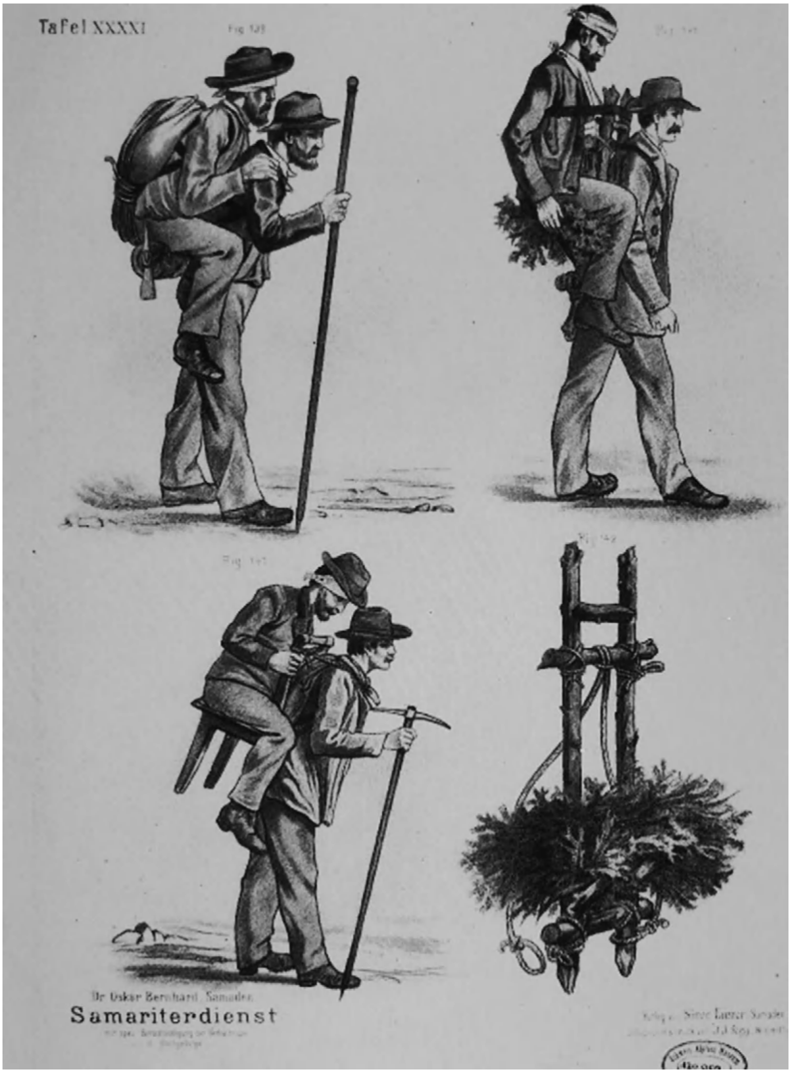
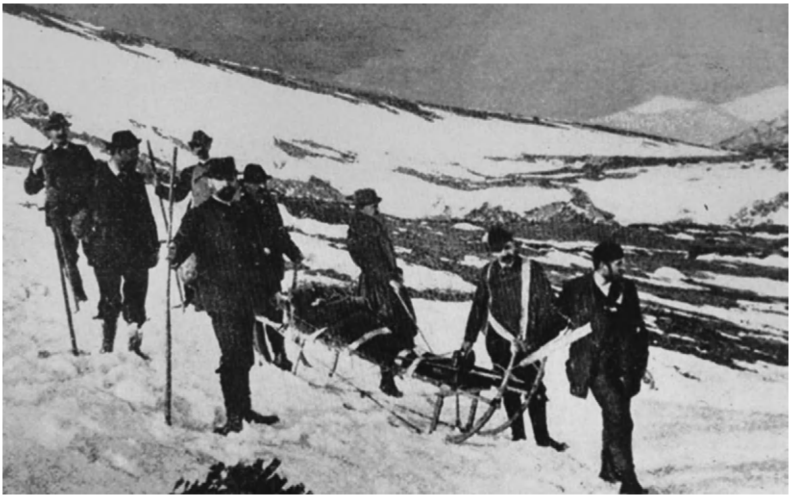


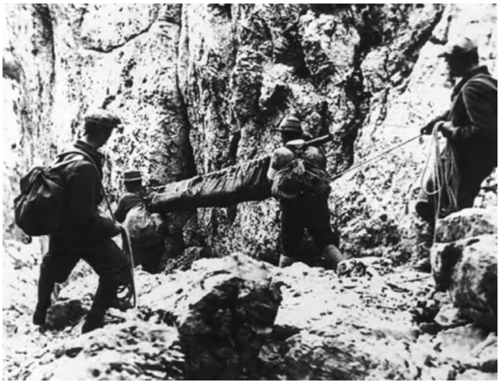
Fig. 1.4 Swiss improvised stretcher in the mountains

Decades later, between approximately 1896 and 1938 (the "founding era"), the first "alpine reporting stations" were established at mountain refuges. These were equipped with basic rescue equipment, and, occasionally, mountaineers were instructed in the use of these devices. From 1880, the Austrian Alpine Club's mountain guide training included a subject on "First Aid". In 1894, the "alpine distress signal" was introduced, and in 1896, the Austrian Alpine Club founded the "Alpine Rescue Committee".

The year 1896 is of particular significance. Following an avalanche accident in Schneebergdörfl on the Rax near Vienna, the first alpine rescue team in the Eastern Alps was established (Fig. 1.5). For a long time, the pole stretcher remained the only means of alpine casualty transport, even in steep, rocky terrain (Fig. 1.6). By



▪ **Fig. 1.5** Rescue team on the Rax, 1896



▪ **Fig. 1.6** Pole stretcher of the German and Austrian Alpine Club

the outbreak of the First World War, the newly established "mountain rescue societies" in Austria had recovered a total of 25 fatalities. Even before the turn of the century, the first textbook on accident prevention and emergency management in the mountains had appeared. *The Dangers of the Alps* was written by a Viennese physician and mountaineer, Emil Zsigmondy, and owing to its brilliance, it remained the standard reference work for decades and ran to numerous editions.

Shortly before the outbreak of the First World War, Professor Stiegler, a physiologist from Graz, developed a prototype of a mountain stretcher that has remained a core component of every mountain rescue station's equipment to this day. The Stiegler mountain stretcher was a collapsible wooden construction in which the casualty could be carried in a semi-seated position or in an anti-shock position with elevated legs. In addition, it could also be lowered by rope.

During the interwar period, several further developments of the mountain stretcher were tested. For example, the German Wehrmacht produced a steel tube construction, the "mountain rescue sledge". This could be separated in the middle for easier transport and could be fitted with ski-like runners for winter or large wheels for summer use (▪ Fig. 1.7). However, all these gallant efforts generally failed because the remote alpine accident site was reached far too late for a living outcome. As a result, the mountain rescue services of the "founding era" were usually only a recovery service for the deceased.

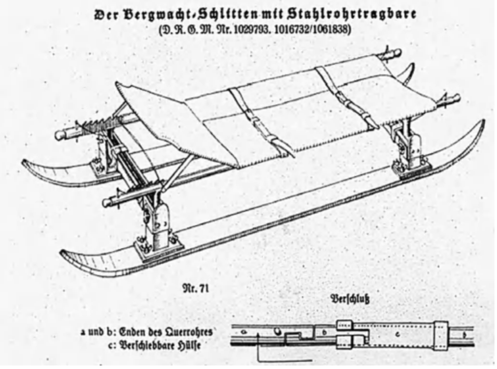

Der Bergwacht-Schlitten mit Stahlrohrtragbare
(D.R.G.M. Nr. 1029793. 1016732/1061838)
Nr. 71
Verſchluß
a und b: Enden des Querrohres
c: Verſchiebbare Hülſe
a
b
c
b

Fig. 1.7 Bavarian mountain rescue sledge

1.1.3 Era of the Development of Mountain Rescue Equipment

During both World Wars, a particularly brutal form of warfare was devised: the relentless trench warfare in high mountain regions. One of the principal military centres for this was the Army High Mountain School in St Johann in Tyrol. The equipment and techniques developed there, under the guidance of medical officer and Füssen-based general practitioner Fritz Rometsch soon became standard equipment for modern alpine rescue and are still in use worldwide today. These include the steel cable device, the mountain stretcher, and the Akja. Another notable piece of equipment was the carrying and abseiling harness developed by Munich's Ludwig Gramminger, the "Gramminger seat" (Fig. 1.8).

In 1946, the Austrian Mountain Rescue Service was founded. Two years later, the first international mountain rescue conference in Europe took place in the Wilder Kaiser (Stripsenjoch) and in Obergurgl (Rotmoosferner). As similar technical developments in rescue equipment had also taken place in other Alpine countries—most notably Switzerland, Germany, and France—this first cross-border meeting was of particular significance. It led to the founding of the International Commission for Alpine Rescue (IKAR; English: International Commission for Alpine Rescue [ICAR]) in May 1956 at Bolzano. The first president was the physician Rudi Campell from Pontresina, Switzerland. Today (2025), ICAR consists of almost 150 member organisations from over 40 countries and includes, among others, a very active medical commission that regularly publishes guidelines (International Commission for Mountain Emergency Medicine—ICAR MedCom).

The revolutionary developments in equipment during the middle of the last century initiated a fundamental paradigm shift in mountain rescue. Instead of an alpine body recovery service, alpine rescue moved towards a life-saving first aid provider directly at the site of the incident. This marked the birth of alpine emergency medicine.

1.1.4 Era of Mountain Air Rescue

Initially, in the 1950s, fixed-wing aircraft of the Piper Super Cub type equipped with snow skis were used in Switzerland and later in Austria. During the major avalanche disasters of 1953 in the Gastein Valley and the Großes Walsertal, large American Sikorsky military helicopters were used for the first time to transport avalanche dogs, doctors, and rescue teams into the disaster areas.

Later, mainly light and small helicopters, such as the Bell 47, JetRanger, Alouette III, Bell UH-1D, and BO105, were deployed by the military, police, and private companies, primarily in Switzerland, Austria, Germany, and France.

Following the example of the German Automotive Club (Allgemeiner Deutscher Automobil-Club—ADAC), Austria's first emergency medical helicopter was commis-

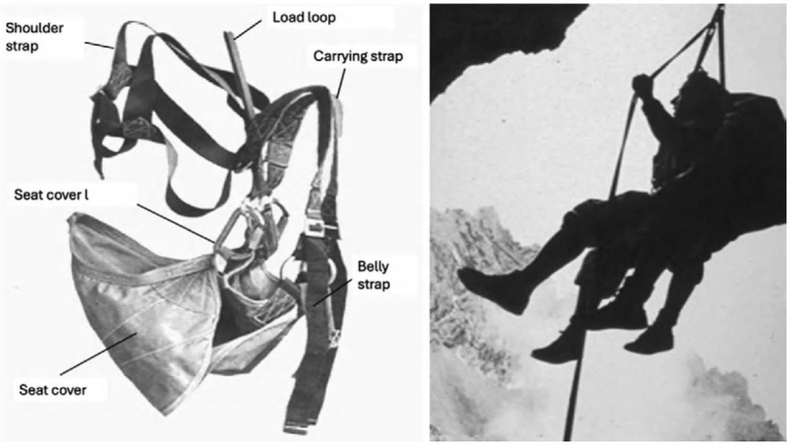

Shoulder strap
Load loop
Carrying strap
Seat cover l
Belly strap
Seat cover

Fig. 1.8 “Gramminger seat” of the Bavarian Mountain Rescue Service

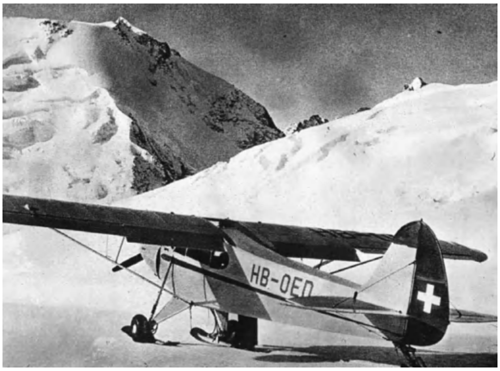


Fig. 1.9 Piper Super Cub with snow skis, 1956

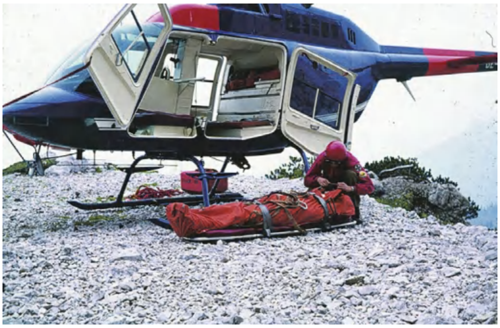
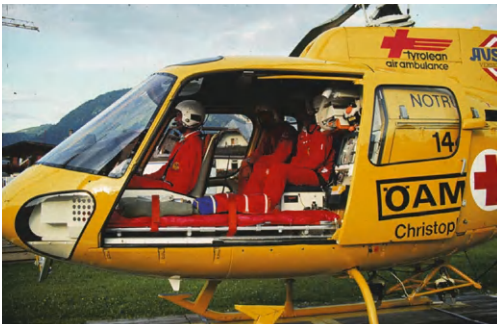


Fig. 1.10 JetRanger after a successful winch rescue, 1974


Tyrolean air ambulance
NOTR
14
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Christop

Fig. 1.11 Three-person crew in the Ecureuil B1, 1985

sioned in Innsbruck on 1st July 1983 by the Austrian Automobile, Motorcycle and Touring Club (ÖAMTC). Today, there are 16 further yellow Christophorus emergency medical helicopters, as well as several other private medical emergency helicopter service providers. Today, assistance in alpine terrain without helicopter support is inconceivable—true to the motto: “No air rescue, no mountain rescue; no mountain rescue, no air rescue”.

The tourism-driven density of emergency medical helicopter systems in Tyrol is now almost a cause for concern and will likely only be curbed in future by economic constraints (■ Figs. 1.9, 1.10, 1.11, and 1.12).

ÖAMTC
© Günther Sumann

■ **Fig. 1.12** H135 (EC135) of the ÖAMTC Air Rescue Service. (With kind permission of G. Sumann)

1.1.5 Era of Electronic Aids

To reduce the long time between an emergency in mountain terrain and alerting helpers, the Swiss Alpine Club installed Hasler AG hut telephones for the first time in 1934. This analogue electronic system enabled communication via radio from mountain huts to various selectable telephone subscribers in the valley.

It was not until 1983 that the digital Motorola DynaTAC mobile phone came onto the market, followed by the D-Netz in 1990, and finally the Apple smartphone in 2007. Today, communication is only one of the features, along with a camera, access to the Internet, a navigation system, digital maps with your live location, weather forecasts, and more.

Today, professional control centres in all European Alpine regions can be reached via the mobile networks. Some centres are very well developed. For example, the emergency application SOS-EU-ALP transmits GPS location data and medical emergency information in parallel with the telephone call. The mobile phone has now become the strongest link in the rescue chain and has saved many lives.

The precise location of injured, buried, or stranded individuals is facilitated by electronic devices. The first avalanche transceivers were produced by Skadi (1972), Pieps (1968), and Ortovox (1980). Today, modern devices operate successfully at 457 MHz with three antennas. In 1983, the RECCO system was introduced, with reflectors installed in ski boots or other clothing, and is now increasingly used for missing-person searches from helicopters as well as in avalanche rescue. Since around 2020, mountain rescue teams have used mobile phone tracking and drones equipped with optical and thermal imaging cameras, especially during search operations. The future must combine human common sense and a sense of responsibility!

1.1.6 Development of Mountain Medical Societies

Internationally, the UIAA MedCom (Medical Commission of the Union Internationale des Associations d'Alpinisme) leads on prevention, the ICAR MedCom (Medical Commission for Alpine Emergency Medicine) on emergency medicine, and the ISSM (International Society for Mountain Medicine) on high-altitude medicine. In German-speaking countries, the ÖGHAM (Austrian Society for Mountain and High-Altitude Medicine), BExMed (German Society for Mountain and Expedition Medicine), and the Swiss Society for Mountain Medicine (SGGM) are all very active. Various diplomas can be obtained through these societies (■ Fig. 1.13).

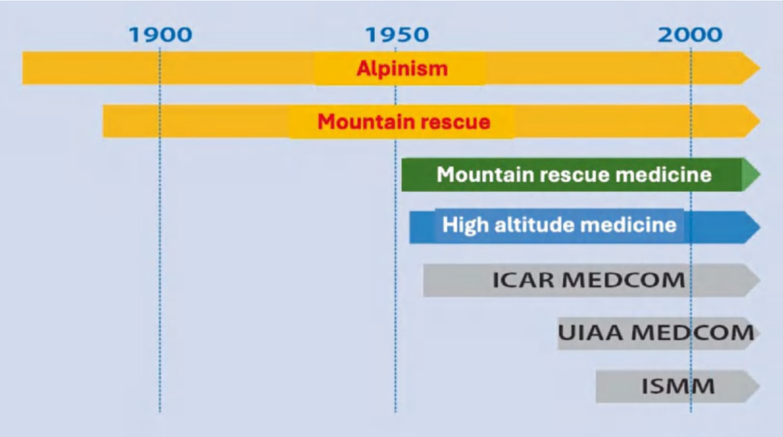


Fig. 1.13 Timeline of the history of mountaineering and mountain rescue

1.2 History of Medicine at High and Extreme Altitudes

Altitude medicine followed a completely different course of development. 'Since the air is so thin up there' and humans have no real place on high mountain. Humans can develop altitude sickness and even die; not surprisingly, the scientific community showed little interest in high and extreme altitudes.

1.2.1 Early Reports of Altitude Sickness

All cultures that settled in high mountain regions report altitude-specific physical complaints, especially headache, nausea, vomiting, and shortness of breath. One of the first to describe this symptomatology was the Spanish Jesuit José de Acosta, working in the Andes in 1590. Similar accounts exist from Asia.

Generations of physiologists, such as Paul Bert, Angelo Mosso, Nathaniel Zuntz, and many others, conducted research in hypobaric chambers and high-altitude laboratories on the effects of the physical phenomena of altitude, resulting in some rather peculiar theories about the influence of altitude on the human body. Anecdotal and often imaginative accounts can be found from all the world's high mountain regions, such as this one from the district physician of Mittersill:

> » During the Glockner expedition in 1800, about a dozen scientists could find no explanation for the fact that several gentlemen, not particularly accustomed to the mountains, developed headaches and occasional dizziness. Perhaps it was related to the fact that the gentlemen quenched their thirst with wine diluted with water. (M. Hutter 2013, personal communication)

However, neither physicians nor physiologists showed much interest in life and survival at high altitude, though there was one notable exception: Thomas Holmes Ravenhill (1881–1952). He was a mining doctor in northern Chile, whose descriptions of altitude sickness published over a century ago are remarkably similar to those of today:

> A majority of newcomers … wake up the next morning with a severe frontal headache … any attempt at exertion increases the headache, which is nearly always confined to the frontal region. (Ravenhill 1913)

1.2.2 A National Tragedy as the Catalyst for Modern Altitude Medicine

Towards the end of the nineteenth century, the British Empire was past its zenith and already beginning to dissolve. It triggered a collective depression in the British national psyche. At that time, a fateful opportunity arose to at least compensate for the wounded national pride on a sporting level—the "conquest" of the North and South Poles was at stake. A relentless race between nations ensued. For Britain, this was to end in tragedy. On 6th April 1909, the American Robert Edwin Peary became the first person to reach the North Pole with sled dogs, and the Norwegian Roald Engebregt Gravning Amundsen stood at the southernmost point of the Earth on 14th December 1911. The Briton, Robert Falcon Scott, had set out before Amundsen but arrived at the South Pole later on 18th January 1912. On seeing the remains of the Norwegian South Pole camp, he acknowledged that they were not the first. None of the British team survived the return journey.

Thus, only one goal remained to soothe this bitter national humiliation. The "third pole", the 8848 m high summit of Mount Everest, was still unclimbed, but it seemed achievable in the light of experience gained by the previous British expeditions in 1921, 1922, 1924, 1933, 1935, 1936, 1938, 1950, and 1951. In June 1924, Edward Norton had to turn back at an impressive 8572 m without supplemental oxygen to save his life (◘ Fig. 1.14): "I was nearly at my limit and moving far too slowly to reach the summit".

◘ **Fig. 1.14** On 3rd June 1924, Edward Norton had to turn back at 8572 m, just below the summit of Everest, without supplemental oxygen, in order to save his life. (Photograph by Howard Somervell)

No systematic research in high-altitude medicine was conducted during this period. Although Barcroft formulated the classic definition of acute mountain sickness in 1925, and the Peruvian Carlos Monge described the "chronic mountain sickness" named after him in 1928, these were rare, isolated contributions.

The Sherpas called bottled oxygen "English air", which Finch used as early as 1922. In 1933, four climbers on Mount Everest reached an altitude of 8534 m without oxygen. In 1938, Lloyd and his companions ascended to 8230 m with oxygen cylinders but did not progress any faster than without oxygen. The equipment was still too primitive and, above all, far too heavy to provide any advantage when climbing. Ultimately, the Second World War brought all further summit attempts to a halt.

1.2.3 High-Altitude Medicine as the Decisive Factor in the Final Metres

In the spring and autumn of 1952, the English faced their next potential disaster. A strong, highly motivated Swiss team, equipped with an innovative oxygen-giving apparatus, was on the verge of finally reaching the summit that year. Had the Swiss succeeded, it would have amounted to a national catastrophe for England. Raymond Lambert and the young Sherpa Tenzing Norgay, together with two other Swiss climbers, reached the final camp at 8400 m, aided by intermittently breathing bottled oxygen. The next morning, they managed to escape downwards only with the greatest difficulty. The reasons for retreat were that the oxygen equipment was unsuitable as it could not be used during climbing due to the high inspiratory and expiratory pressures required. In addition, the rigid mouthpieces prevented any head movement, and none of the Swiss had a stove in their pack, so melting snow was impossible. Thus, in this critical phase just below the summit of Mount Everest, there was absolutely nothing to drink, and severe dehydration was taking its toll.

The American high-altitude physician Houston later commented succinctly:

> » Thus the Swiss, who were born and bred in the mountains and almost certainly had a team whose technical climbing ability was superior to that of the British, failed primarily because insufficient attention had been given to two critical physiological factors: oxygen and hydration. (Houston et al. 2005)

By contrast, a year later, Hillary reports on the dinner on 28th May 1953 at the final camp:

> » Pint after pint of hot lemon drink crammed with sugar, followed by great mugs of lemonade from 11 p.m. to 1 a.m., and finally more fluid for breakfast, trying to get as much moisture into ourselves as we could. (Houston 1998)

The British in 1953 owed much to the Swiss's failure in 1952, for it must surely count among the great moments in expedition mountaineering that the members of the 1952 Swiss expedition generously supported the British team with advice and invaluable experience. And then there was Lambert's young companion, the Sherpa Tenzing Norgay, who was intimately familiar with the terrain when, a year later, he set out with Hillary towards the summit.

After decades of failure and national frustration, the great success finally came on 29th May 1953, and, of all days, it coincided with the coronation of the English Queen! The success of the expedition owed most to a previously completely unknown physician, Lewis Griffith Cresswell Evans Pugh.

Pugh, a typical Welshman, was a physiologist with a small British research expedition that, in May 1952, travelled to the Nangaon La (4720 m) and was travelling towards the Menlung La (6100 m) in the area of the then still unclimbed Cho Oyu. The expedition was focused on a very specific goal, the summit of Mount Everest. For the first time, he and his team systematically conducted comprehensive studies on, among other topics:

- Respiration at high altitude and oxygen uptake during climbing—critical aspects relevant to previously unresolved questions regarding the use of supplemental oxygen
- Fluid balance at altitude and the importance of fluid intake
- Energy balance and nutrition
- Cold protection with clothing and tents

One detail of his work stands out: He was the first to investigate climbing rates (vertical metres per hour) under different oxygen flow rates, in both open and closed systems, and during both intermittent and continuous bottled oxygen use. These would identify the optimal technique. As a result of this field study, Pugh instructed that Hillary and Tenzing should ascend with an open oxygen system at a flow rate of 3 L/min. This enabled them to achieve an impressive 192 vertical metres per hour in the summit area of Everest, whereas Lambert and Tenzing, a year earlier on the same route and under comparable snow conditions, managed only 71 vertical metres per hour using a closed system and intermittent oxygen breathing from cumbersome equipment that was completely impractical for climbing. It should be noted, however, that Lambert and Tenzing were also, as mentioned previously, severely dehydrated.

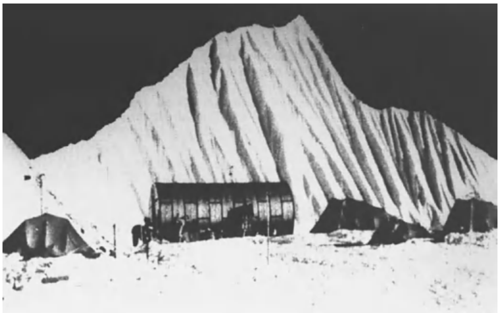
It is now widely accepted that the summit success of Hillary and Tenzing was largely due to Pugh's findings on Cho Oyu: "In fact without this work it is doubtful if the mountain would have been climbed" (West 1998). Griffith Pugh's research expedition in the pre-monsoon of 1952 is therefore often regarded as the birth of modern high-altitude medicine, and Pugh himself as the pre-eminent figure in high-altitude medicine of the twentieth century. His historical significance, in contrast to physiologists such as Mosso, Zuntz, Bert, and others, who are sometimes mistakenly referred to as high-altitude physicians, is best illustrated by the following episode:

Forty years after the first ascent of Everest, in May 1993, the British Queen invited all members of the successful expedition to a reception. During the event, Dr Michael Ward, the expedition doctor in 1953, spoke:

> » We have been hearing a great deal this evening about the extraordinary brilliant leadership provided by Sir John Hunt on the 1953 Everest expedition, but there had been eleven previous expeditions to Mount Everest, many of which had excellent leaders, and they failed. We have been hearing about the great skill of our climbers, but there had been many highly skilled climbers on previous Everest expeditions, yet they failed to get to the summit. We have been hearing about the brilliant logistics, but there had been other well organised and planned expeditions which all failed. What I want to talk about tonight is the most important reason why the 1953 expedition to Mount Everest succeeded where all its predecessors failed, and this is the work of the unsung hero of Everest … Dr. Griffith Pugh. (Tuckey 2013)

1.2.4 The Silver Hut and Other High-Altitude Medicine Projects

In 1961, under the leadership of Griffith Pugh, the legendary Silver Hut expedition took place at the 5800 m high Mingbo La near Everest, lasting almost 6 months and involving several young high-altitude physicians, such as John West and Jim Milledge, who would go on to have distinguished careers. For the first time, acclimatisation at extreme altitude could be studied and the complex phenomenon of high-altitude deterioration elucidated (◘ Fig. 1.15).



◘ **Fig. 1.15** The Silver Hut, 1961

In addition, permanent high-altitude research stations were established in the world's high mountain ranges (for example, the Capanna Regina Margherita and Refuge de Vallot in the European Alps). Mount Everest itself became the "testing place" for renowned scientific expeditions—milestones for the still young discipline of high-altitude medicine, with the recurring realisation that "up there, where the air is so thin", many questions remain open and unresolved.

Mount Everest, "the Testing Place"

- 1981: AMREE—8848 m
- 1985: Everest II—"8848 m" (simulated Everest ascent in the hypobaric chamber)
- 1997: Everest III/F—"8848 m" (simulated Everest ascent in the hypobaric chamber)
- 2009: Everest—8848 m (Caudwell, British)

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2

Terrestrial and Cosmic Radiation

Ulrike Prettenhofer and Michael Groher

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Introduction

The age of our universe is estimated to be 14 billion years. The Earth, at around 4.5 billion years old, is relatively young, and it took another 4 billion years before the first living organisms could develop on it. Humans only started to exist on this planet about 1 million years ago.

As early as 6000 years ago, the Sumerians observed stellar explosions. Remnants of a supernova explosion described by the Chinese in 1054 are still visible today as the Crab Nebula, which emits gamma rays and X-rays (Grupen 1994). This highly energetic radiation, which originates in the centres of active galaxies, is largely absorbed by the Earth's atmosphere, but can be detected as particle showers using giant telescopes or measured by satellites outside the atmosphere.

2.1 Physical and Biological Principles

Since its formation, the Earth has been exposed to cosmic radiation. The planet itself emits radiation due to the uranium and its radioactive decay products contained within it. All life on this planet has, over millions of years, evolved and adapted to this natural radiation exposure.

The term "radiation" refers to the propagation of particles or waves. These are classified as ionising or non-ionising depending on their energy. The unit of energy is joule (J). In cases of human exposure to radiation, both the absorbed dose and the type of radiation are relevant. The absorbed dose, i.e. the energy absorbed per unit mass, is measured in grey (1 Gy = 1 J/kg). Interaction with matter causes direct (by displacing atoms) and indirect (by forming free radicals) damage to molecular structures (Krieger 2007). Complex molecular repair systems can repair this damage. However, depending on the duration and intensity of radiation exposure, persistent somatic and genetic changes may also occur. The relative biological effectiveness, measured in sievert (Sv), depends on the type of radiation and the absorbed dose. For alpha, proton, and neutron radiation, it is several times higher than for gamma, X-ray, or electron radiation (Krieger 2007). The different types of radiation—ionising and non-ionising—are listed in ▣ Table 2.1.

▣ **Table 2.1** Types of radiation (ionising and non-ionising)

Electromagnetic radiation	**Wavelength (m)**
Radio waves	$1–10^{3}$
Microwaves, infrared radiation	$10^{-2}–10^{-5}$
Visible light	10^{-6}
UV radiation	UVA (400–315) 10^{-9} UVB (315–280) 10^{-9} UVC (280–100) 10^{-9}
X-rays	10^{-10}
Gamma radiation	$10^{-11}–10^{-14}$
Cosmic radiation	10^{-15}
Particle, corpuscular radiation	
Alpha radiation (2 protons +2 neutrons)	
Beta radiation (electrons, positrons)	
Neutron radiation	

Human exposure to radiation consists of natural radiation (terrestrial radiation, cosmic radiation, and solar radiation) and artificially generated radiation (medicine, industry, and research).

2.2 Natural Radiation

Natural radiation consists of terrestrial and cosmic radiation.

2.2.1 Terrestrial Radiation

Even before the formation of our solar system, radionuclides were produced which, due to their very long half-lives, are still present in the Earth's crust today. The radiation emitted mainly by potassium as well as uranium and its radioactive decay products in the Earth's crust is referred to as terrestrial radiation and occurs worldwide at varying intensities. The annual exposure to natural radionuclides in soil, rocks, and air (radon) in Germany averages 2.1 mSv/year, but, depending on place of residence, diet, and lifestyle, can reach up to 10 mSv/year (BfS 2023).

In general, calcareous soil is less radioactive than, for example, granite, in which uranium can be detected at somewhat higher concentrations (Lazar and Winkler 2006). By far, the highest value of terrestrial radiation has been measured in Iran (Ramsar, radon), followed by India (Kerala, monazite sand) and Brazil (Guarapari, monazite sand) (De Affonseca et al. 2002; Mortazavi et al. 2006; ▣ Table 2.2).

▣ Table 2.2 Natural sources of radiation

Natural sources of radiation	Whole-body effective dose (mSv/year)
Cosmic radiation (sea level)	0.3
3000 m	1.5
8000 m	20
300 km (space shuttle)	200/flight
Flight Vienna—Rio	0.05/flight
Aircrew	5–6
Terrestrial radiation	0.3
Kerala (India)	30
Guarapari (Brazil)	35
Ramsar (Iran)	130
Ingestion	0.2
Radon inhalation	1–2
Radon therapy Gastein	2–5/course
20 cigarettes/day	100 (lung dose)

The uranium fission product and noble gas radon (Rn) accounts for more than one third of the annual radiation exposure of the population due to its alpha radiation. This odourless gas migrates from the ground into the interior of buildings through permeable construction materials (cracks, joints, pipe penetrations, etc.) in the basement area, where it can accumulate at elevated concentrations, especially when room heating is used, if ventilation is inadequate. Once inhaled, the gas exerts its effect in the lungs via its radioactive decay products, contributing to the development of lung cancer as a result of DNA damage. As early as 1988, both the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) classified radon as a human carcinogen.

A survey conducted in Austria in 1989 by the Central Statistical Office for the Atlas of Causes of Death revealed an increased mortality rate from bronchial carcinoma in the region around Umhausen in Tyrol. Investigations showed that a landslide more than 8000 years ago had deposited large masses of uranium-bearing granite gneiss as debris, resulting in exceptional porosity and permeability of the soil and, consequently, increased exhalation of the carcinogenic uranium decay product radon (Ennemoser et al. 1994; Purtscheller et al. 1997). Research findings from Langtang Himal in Nepal, with a similar geological setting, appear to support this hypothesis (Purtscheller et al. 1995; Choubey et al. 2005).

An increase in radon concentration in buildings has been observed due to energy-saving construction measures. In Austria, the average annual indoor radon exposure from inhalation is 1–2 mSv, representing the largest proportion of natural radiation exposure.

Nearly 500 years ago, the effects of radon on miners in Schneeberg (Saxony) were described by Paracelsus in his three books *On Miners' Disease and Other Mining Illnesses* (Paracelsus 1533). Even today, strict regulations in mining and tunnel construction focus on radon exposure.

Radon exposure, which is promoted as a therapy for respiratory and musculoskeletal disorders in various healing tunnels and spas, and whose analgesic effect is presumably due to its anti-inflammatory and radiotherapeutic action, actually results in a multiple of the annual natural radon exposure after a course of several weeks (▣ Table 2.2).

In contrast, the exposure from natural radionuclides (14C, 40 K, 210Po, 238 U) ingested via water and food is only about one tenth of the radon exposure (Krieger 2007). However, regional variations in water concentration can occur, with values up to 100,000 times higher when comparing groundwater and spring water with mineral springs. Sources with such high activity concentrations are therefore not approved as drinking water.

Currently, research is being conducted to determine whether smoking may contribute to lung cancer not only through chemical carcinogens but also as a result of radioactivity due to the high polonium content in tobacco plants, which preferentially absorb this uranium decay product from the air and the associated alpha radiation (Muggli et al. 2008; Winter and Franza 1982; Zaga et al. 2021).

2.2.2 Cosmic Radiation

Cosmic radiation, or high-altitude radiation, refers to highly energetic atomic particle radiation from space (both intra- and extragalactic), which was first measured in 1912 from a hot air balloon by the Austrian physicist Viktor Hess at an altitude of 5000 m. The interaction of primary cosmic radiation with the Earth's atmosphere (mainly oxygen and nitrogen atoms) produces secondary radiation (e.g. muons, pions), with intensity maximum at an altitude of approximately 15 km, of which only a small fraction reaches the Earth's surface (Grupen 1994).

Due to the Earth's magnetic field, this particle shower is distributed unevenly: radiation exposure is five times higher at the poles than at the equator. During periods of intense solar surface activity with the emission of gamma radiation, exposure, especially in space travel, can increase by many times for several hours. The annual dose of cosmic radiation measured at sea level averages 0.3 mSv, which is similar to the annual dose from terrestrial radiation.

This radiation causes ionisation of atoms and molecules in our bodies, leading to chemical or biochemical reactions and thus to damage to the genetic material in cells.

However, cosmic radiation increases with altitude. At 3000 m, it is approximately 1.5 mSv/year, while at the Capanna Regina Margherita at 4554 m, it is about 2.6 mSv/year. For the hypothetical warden of an "Everest Summit Hut", exposure would already exceed the annual occupational exposure limit of 20 mSv permitted in Austria and Germany. In 2012, the US Mars rover Curiosity collected data showing that a manned mission to Mars would result in a radiation dose of about 660 mSv for the crew for the return journey alone (Zeitlin et al. 2013).

2.2.3 UV Radiation

By far, the most influential natural source of radiation for humans is the sun, although only a small proportion of the UV radiation it emits is ionising (◘ Fig. 2.1). This component of the electromagnetic spectrum, known as UVC, is currently still largely absorbed by the ozone layer (Lazar and Winkler 2005). However, UVA and UVB rays are also capable of causing DNA damage in skin cells. Due to the growing interest in sports-related leisure activities, skin cancer is becoming an increasing public health problem (Moehrle 2008).

Studies conducted on recreational athletes have shown that UV exposure (measured using dosimeters attached to headbands over the course of a year), due to altitude (approximately 10% increase in UV radiation per 1000 m of elevation) and the strong reflection of radiation from snow and ice, can reach up to 20 times the UV limit value set by the American Conference of Governmental Industrial Hygienists (ACGIH) (Moehrle et al. 2003; Rigel et al. 2003; Sohrabi and Esmaili 2002).

UV-induced skin damage is discussed in ► Chap. 44, and ► Chap. 45 addresses, among other things, the effects of UV radiation on the eyes at high altitudes.

◘ **Fig. 2.1** The most important natural source of radiation for humans: the sun. (Image rights: W. Domej)

2.3 Anthropogenic Radiation Exposure

In addition to industry and research, medicine is the largest contributor to anthropogenic radiation exposure (Krieger 2007). The health benefits and risks of all types of radiation applications must be carefully balanced to justify any examination or treatment.

In contrast, radiological emergencies are rare but can have catastrophic consequences. An early warning system for radiation serves to provide the public with information and behavioural recommendations. The radioactive fallout of recent decades, beginning with the long-underestimated global contamination following negligently conducted nuclear tests in the 1950s and 1960s, up to the catastrophic consequences of Chernobyl and Fukushima, varies regionally. It manifests both as ground radiation from deposited radionuclides and through ingestion of radioactively contaminated food (mainly caesium-137, with a half-life of 30 years, which is still detectable in mushrooms, berries, and the meat of wild animals). The radioactivity remaining in the soil has now decreased to about 0.01 mSv annual exposure for humans. ◘ Table 2.3 presents the

◘ **Table 2.3** Artificial sources of radiation

Examination/treatment	Effective dose (whole body) (mSv)
Chest X-ray	0.05–0.1
Mammography	0.5
CT chest	8
CT abdomen/pelvis	10
Annual medical dose (Austria/Germany)	1.3
Annual dose from radioactive fallout (Germany/Austria)	0.01

▫ **Table 2.4** Radiation damage: lethal dose

Dose from single whole-body exposure (mSv)	Radiation effects
500	Changes in blood count
1000	Nausea, vomiting, hair loss
2000	10% mortality, diarrhoea, weight loss
3000	20% mortality, bleeding, inflammation
4000	50% mortality within 6 weeks
6000	90% mortality
20	Annual limit for medical staff (AT)

various artificial sources of radiation and their effective dose to the body.

Radiation damage can occur even at low doses, but increases with both dose and duration of exposure. The lethal dose (LD50/30 days [50% mortality after 30 days]) varies between species and, in humans, is 4 Sv after a single exposure (▫ Table 2.4).

Conclusion

The total annual exposure to radioactive radiation relevant to humans in Europe is 3–5 mSv. The contribution from natural radioactivity, averaging 2–3 mSv/year, is somewhat higher than that from medical sources at 1.3 mSv/year. With the exception of regional variations, radon gas represents the largest natural source of radiation. Cosmic radiation increases with altitude, but even in the highest permanently inhabited areas, it never reaches levels harmful to health. In recent years, there has been a marked increase in diagnostic radiation exposure in medicine, despite successful reductions in the dose per individual examination due to ongoing modernisation of equipment.

It is perhaps worth mentioning that every person possesses a certain “radiation” not only due to their character but also as a result of the decay of specific elements (e.g. potassium) in the body. However, this is relatively low, averaging 50 becquerels per kg (1 Bq = 1 nuclear decay per second); by comparison, the current EU limit for foodstuffs is approximately 600 Bq per kg.

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Physics of Moderate, High, and Extreme Altitudes: The Earth's Atmosphere

Wolfgang Domej and Günther Schwaberger

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3.1 Development of the Earth's Atmosphere and Oxygen Enrichment

The origins of the present-day Earth's atmosphere date back approximately 4 billion years. Free oxygen was not present in the earliest atmospheres (the first and second primordial atmospheres) around 3.6 billion years ago. The first primordial atmosphere was also completely anoxic and consisted mainly of heallium (He) and hydrogen (H) elements that subsequently escaped into space.

The so-called second primordial atmosphere consisted of gases released from the Earth's interior in association with liquid magma. These were composed of H^+, CO_2, N_2, NH_3, CH_4, and water vapour. The initial complete absence of free oxygen was probably due to the reducing effect of iron-rich rock formations, with the abundant divalent iron chemically binding all available oxygen (O_2). The first energetic utilisation of sunlight by primitive bacteria (cyanobacteria), which were able to produce oxygen via photosynthesis, occurred in the primordial ocean 3–3.5 billion years ago. This enabled the gradual build-up of an oxygen-containing atmosphere, thus creating the prerequisites for the development and existence of higher organisms (Schidlowski et al. 1974).

According to the endosymbiotic theory, nucleated anaerobic primordial cells incorporated O_2-utilising bacteria, which, protected by a cell membrane, could supply a host cell with energy very efficiently. Over billions of years, this symbiosis led to the development of mitochondria, which are characteristic of animal cells (Gray et al. 1999). Other primordial cells also incorporated cyanobacteria, which, through evolutionary processes, developed into O_2-producing chloroplasts. These ultimately gave rise to the typical plant cells capable of photosynthesis as we know them today (Wernegreen 2012).

3.2 Atmospheric Envelope

The current atmospheric oxygen concentration (O_2 fraction/F_iO_2 in the entire atmosphere: 0.21) first appeared about 350 million years ago. Since then, there have been repeated fluctuations in atmospheric O_2 content. The maintenance of the present-day gaseous atmosphere is solely due to green plants, which, through the process of photosynthesis (light-absorbing pigment chlorophyll), break down carbon dioxide from the air, use the carbon component to build their own cell structures, and release the oxygen, which they cannot use, into the atmosphere.

In this way, plants continuously compensate for the enormous oxygen losses caused by decay and oxidation. Without this oxygenic photosynthesis, free oxygen would disappear from the Earth's atmosphere in just under 3000 years. Strictly speaking, however, oxygen is not synonymous with the life process itself, but rather with a high energy yield. Eukaryotic organisms (unicellular or multicellular life forms) whose cells possess a nucleus require oxygen to efficiently produce adenosine triphosphate (ATP), the fundamental molecule essential for energy transfer. Atmospheric conditions at high altitude, whether during acute hypoxic exposure or prolonged stays at altitude, demand a complex physiological interplay between numerous functional systems within the organism. The vertical structure of the atmosphere is defined by the parameters of temperature, air pressure, and air density. Within the troposphere (the lowest layer of the Earth's atmosphere), the composition of the air is particularly complex. Up to an altitude of 15,000 m, 90% of the total air mass and nearly all the water vapour in the Earth's atmosphere (clouds, precipitation) are contained. This is where actual weather phenomena occur. The Earth's troposphere is not uniform due to the planet's rotation and extends up to approximately 18,000 m at the equator and about 8000 m at the poles, with the troposphere at the poles being up to 2000 m lower in winter than in summer. The current atmospheric gas composition consists of the main components oxygen (20.95%), nitrogen (78.0%), and argon (0.93%), as well as a negligible proportion of other noble gases (neon, krypton, xenon), trace gases of organic origin, sulphur and nitrogen compounds, hydrogen, gaseous radicals (ROS), soot and sand particles, and traces of radon (◘ Table 3.1), with the proportional composition of the air mixture up to an altitude of 11,000 m corresponding to that of the lower atmospheric layers; i.e. the percentage of O_2 molecules remains unchanged, while the absolute number per unit volume decreases with increasing altitude above sea level.

By convention, geographical altitudes are generally classified as moderate (1500–3000 m), high (3000–5500 m), and extreme (above 5500 m). The effects of altitude on human physiology have been extensively studied under both natural and simulated conditions.

Destinations renowned for their exceptional altitude, such as La Paz (3627 m) in Bolivia, the highest capital city in the world, or Lhasa (3650 m) in Tibet, already require the capacity for long-term adaptation to a markedly O_2-deficient atmosphere. In order to survive permanently at these altitudes, a complex adaptation process of the organism to the hypoxia of this altitude (acclimatisation) is required. Also, certain genetically determined physiological trait profiles are advantageous (Ramirez et al. 1999).

In this context, therapeutic altitudes have also been defined: these are elevations between 1500 and 2200 m. Therapeutic altitudes are those at which individuals still exhibit normal arterial haemoglobin O_2 saturation (S_aO_2). The positive health-promoting and invigorating (i.e. strengthening) effects of therapeutic altitudes have long been utilised by rehabilitation centres and “high-altitude clinics” (e.g. Davos, 1560 m) for patients with bronchial asthma, cardiovascular diseases, or metabolic syndrome. ◘ Table 3.1 illustrates the composition of atmospheric air.

Altitude-related physical parameters determine both the high-altitude atmosphere and climate and can trigger physiological regulatory processes, and, if applicable, pathophysiological mechanisms in the human organism. Key parameters, which are also meteorological elements, include total atmospheric pressure (p_B), inspiratory oxygen partial pressure (p_iO_2), humidity (RH), air temperature (T), air density (ρ), air flow, altitude radiation, cloud cover, and precipitation (◘ Table 3.2).

Values for vertical changes in air pressure are derived from the barometric scale height (BSH). This defines the altitude difference at which a specific decrease in air pressure is to be expected or represents the temperature-dependent vertical distance in which an air pressure change of 1 hPa (= 1 mbar) occurs. Near ground level, the

◘ **Table 3.1** Composition of atmospheric air

Component	**Volume fraction (in %)**
Nitrogen (N_2)	78.0
Oxygen (O_2)	20.95
Argon (Ar)	0.93
Carbon dioxide (CO_2)	0.034
Neon (Ne)	0.0018
Helium (He)	0.0005
Methane (CH_4)	0.00016
Krypton (Kr)	0.00011
Hydrogen (H_2)	0.00005
Carbon monoxide (CO)	0.00002
Ozone (O_3)	0.000007
Xenon (Xe)	0.000003

Table 3.2 Key physical parameters and changes with altitude

Determinants of high-altitude climate	Unit	Change with altitude
Barometric pressure (P_B)	mmHg/hPa	−60 mmHg/80 hPa per 1000 m
Inspiratory oxygen partial pressure (p_iO_2)	mmHg/hPa	−17 mmHg/22.7 hPa per 1000 m
Temperature (T)	°C	−6 °C per 1000 m
Humidity (RH)	%	−25% per 1000 m
Air density (ρ)	kg/m^3	−0.0875 kg/m^3 per 1000 m
Altitude radiation	mSv	+10–20% per 1000 m
Wind speed	m/s	+Wind chill factor
Precipitation	mm/day	+~4500 m depending on cloud height and region

Table 3.3 Temperature-dependent barometric scale heights (m/hPa)

	−15 °C	0 °C	15 °C	30 °C
Sea level	7.5	7.9	8.3	8.8
500 m	7.9	8.3	8.7	9.2
1000 m	8.3	8.7	9.2	9.6
2000 m	9.3	9.7	10.1	10.6
3000 m	10.4	10.8	11.2	11.6

barometric scale height is approximately 8 m, at 5 km altitude 16 m, and at 10 km altitude 32 m (Table 3.3).

The vertical distribution of gas molecules in the Earth's atmosphere is described by the barometric height formula, which reflects the altitude dependence of atmospheric pressure.

The decrease in p_B as well as the inspiratory O_2 partial pressure (p_iO_2) with increasing altitude is not linear, but exponential. Because of the reduction in p_B, the lower compression of the ambient air also leads to a decrease in air density (ρ), i.e. the air becomes “thinner” with increasing altitude (see Table 3.2). The international barometric formula for static pressure P in N/m^2 at altitude H in metres (P_0 = static pressure at sea level = 1013.25 hPa, T_0 = temperature in K at sea level [15 °C = 288.15 K], α = temperature gradient = −0.0065 K/m, $\beta = g/\alpha R_s = -5.255$, where g = mean gravitational acceleration at sea level = 9.8 m/s^2 and R_s = specific gas constant dry air = 287 J/(kgK)) is as follows:

$$P = P_0 (1 + \alpha H / T_0)^{-\beta}$$

3.3 Total Atmospheric Pressure (p_B) and Inspiratory Oxygen Partial Pressure (p_iO_2) at Altitude

Both the total atmospheric pressure (P_B) of the air column and its weight decrease with increasing altitude. For the pressure units, most commonly used in practice, mmHg and hPa (mbar), the following conversions apply:

$$1\,\text{Torr} = 1\,\text{mmHg} = 133.3\,\text{Pa}\,(1.333\,\text{mbar}) = 0.1333\,\text{kPa}$$

$$1\,\text{hPa} = 0.750\,\text{mmHg} = 1\,\text{mbar}$$

Table 3.4 Geometric altitude, total barometric air pressure (p_B) in hPa or mmHg, temperature, air density (ρ), and inspiratory partial pressure of oxygen for dry and humid air (p_iO_2)

Geometric altitude (m)	Air pressure (hPa)	Air pressure (mmHg)	Temperature (°C)	Air density (kg/m³)	p_iO_2 dry (mmHg)	p_iO_2 humid (mmHg)
0	1013.3	760.0	15	1.225	159.2	149.3
1000	898.8	674.1	8.5	1.112	141.2	131.4
2000	794.9	596.3	2.0	1.007	124.9	115.1
3000	701.1	526.0	−4.5	0.909	110.2	100.3
4000	616.4	462.5	−10.9	0.819	96.9	87.0
5000	540.3	405.4	−17.5	0.736	84.9	75.1
6000	471.9	354.2	−23.9	0.660	74.2	64.3
7000	410.9	308.3	−30.4	0.590	64.6	54.7
8000	356.1	267.4	−36.9	0.526	56.0	46.2
9000	307.9	231.0	−43.4	0.467	48.4	38.6

According to Dalton's law, the total atmospheric pressure (p_B) is composed of the pressure components or partial pressures of its constituent gases. Each gas in an inspired air mixture contributes to the total pressure in proportion to its volume fraction (F_i). Thus, $p_B = p_iN_2 + p_iO_2 + p_iCO_2 + p_iH_2O$. The inspiratory oxygen partial pressure (p_iO_2) at sea level averages 159 mmHg, and at 8000 m altitude, it is 56 mmHg. This is calculated as $p_B \times F_iO_2$ ($p_iO_2 = 760 \times 0.21 = 159$ or $276 \times 0.21 = 56$) (Table 3.4).

The total atmospheric pressure (p_B) and its partial pressures are also temperature dependent and thus related to geographic latitude and season. Since cold air is denser and therefore heavier than warm air, p_B increases or decreases more rapidly with vertical displacement in cold air than in warm air.

The decrease in p_B for temperature-expanded air occurs more slowly with increasing altitude than for cold or compressed air. Consequently, the reduction in atmospheric pressure with altitude depends on temperature and, indirectly via gravity, also on topographical location. The closer a high-altitude destination is to the equator, the higher the p_B is at the same elevation.

The influence of temperature is particularly evident on the highest peaks near the poles, such as Ellsworth Mountain (5140 m), Mount Vinson (4892 m), and Mount Tyree (4852 m) in Antarctica, all located just below the 79th southern parallel, or on the summit of Mount McKinley (6194 m) in Alaska, which lies at the 63rd northern parallel.

In addition, local weather conditions play a significant role in atmospheric pressure and the inspiratory partial pressure of oxygen (p_iO_2). If Mount Everest (8848 m) were located at the same latitude as Mount McKinley (6193 m), the highest geographical point on Earth would be inaccessible to humans without supplemental oxygen due

▣ **Table 3.5** Inspiratory and alveolar O_2 pressure conditions at 8848 m (Mount Everest)

p_B Mount Everest (8848 m)	Ø 251 mmHg
p_iO_2 dry	251 × 0.21 = 52.7 mmHg
p_iO_2 humid (water vapour saturated)	(251–47) × 0.21 = 42.7 mmHg
p_AO_2 minus p_ACO_2 (rest)	([251–47] × 0.21)—40 = 2.7 mmHg
p_AO_2 during excessive hyperventilation	([251–47] × 0.21)—10 = 32.7 mmHg

p_B total atmospheric pressure, p_iO_2 inspiratory partial pressure of oxygen, p_ACO_2 alveolar partial pressure of carbon dioxide, p_AO_2 alveolar partial pressure of oxygen

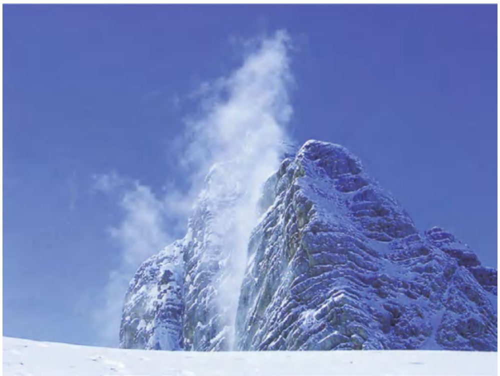
to the extremely low temperatures typically prevailing at this latitude and altitude, which further reduce p_iO_2.

The degree of atmospheric hypoxia and low temperatures at Mount McKinley are indeed comparable to the hypobaric hypoxic conditions found on seven-thousanders in the Himalayas around the 28th southern parallel. ▣ Table 3.5 refers to the average p_AO_2 at the summit of Mount Everest (8848 m), taking into account the necessary conditioning of the inspired gas (water vapour saturation, warming, filtration) and maximal alveolar hyperventilation.

In contrast to vertical pressure differences, horizontal pressure variations, such as those occurring during transitions between high- and low-pressure systems or vice versa, are comparatively minor. For example, the greatest air pressure difference ever recorded at Sonnblick (3111 m) corresponds to an altitude difference of 655 m. The highest weather-related pressure differences in our latitudes are therefore likely to correspond to altitude differences between 500 and 700 m and thus play only a minor role in alpine sports in our region.

3.4 Climatic Influence

In meteorology, total atmospheric pressure (p_B) and high-altitude radiation are the most important climatic elements at altitude, with p_B considered both a cause and a regulatory factor for various weather phenomena. In this context, p_B also exerts a biogenic influence, for example, through large-scale pressure differences between high- and low-pressure areas, which can affect human well-being via various weather phenomena such as the foehn wind.



▣ **Fig. 3.1** Updraft channel with convective cloud formation above the south face of the Dachstein

In this context, physiological processes should be mentioned that can be triggered by sudden fluctuations in air pressure—phenomena known in bioclimatology as weather sensitivity (meteorotropism). However, the influence of air pressure at moderate and high altitudes plays a lesser role in subjective well-being compared to climatic factors such as temperature or precipitation (▣ Fig. 3.1).

Largely independent of prevailing weather conditions, climatic elements can change very rapidly with increasing altitude. For example, high-altitude radiation contains higher proportions of UVB, ambient temperature decreases, the inhaled air becomes drier, and wind speed and thus the subjectively perceived cold stress increase (wind chill factor). Up to a certain altitude, precipitation also increases (◘ Table 3.2).

3.5 Hypoxic Environment

Hypoxia refers to a deficiency of O_2 in the environment or an inadequate supply of O_2 to organs or the entire organism. In contrast, hypoxaemia denotes a reduced O_2 saturation of haemoglobin in the blood, which under certain circumstances can result in critical tissue hypoxia if organ perfusion is borderline (for instance, with coronary and peripheral artery disease).

Depending on the degree of hypoxia and duration of exposure, any form of hypoxia leads to changes in metabolic processes, including energy production at the cellular level. In altitude and sports medicine, hypoxaemia is particularly relevant when caused by hypobaric conditions (terrestrial or "artificial" via reduction of p_B) or normobaric hypoxia ("artificial hypoxia" via enrichment of N_2 in the breathing air or rebreathing systems with CO_2 absorption). Equivalent altitudes under artificial O_2 deficiency conditions (normobaric hypoxic chamber) refer in this context to hypoxic conditions generated at sea level that correspond to the degree of hypoxia at a specific geographical altitude.

According to Boyle's law, the product of pressure and volume of a gas remains constant under isothermal conditions. This means that a rapid decrease in ambient pressure due to a sudden passive ascent (cable car rides, flights in non-pressurised aircraft such as light aircraft, helicopters, and gliders, as well as during paragliding or balloon flights) can cause symptoms due to the expansion of air or gases, manifesting as pain in the jaw or teeth, paranasal sinuses, middle ear (barodontalgia, barosinusitis, barotitis media), or gastrointestinal tract.

Therefore, teeth with fillings or inflammation of the paranasal sinuses or middle ear also pose a risk when staying at unfamiliar altitudes. Moreover, the immediate expansion of all body gases at extreme altitudes can lead to soft tissue swelling and meteoristic bloating. For this reason, gas-producing foods and carbonated beverages should be completely avoided before a rapid passive ascent.

Caution is also warranted in cases of advanced pulmonary emphysema, as a sudden drop in P_B can lead to the maximum possible expansion of the lungs.

The boiling point of water also depends on P_B and thus on terrestrial altitude. Compared to the so-called normal boiling point (normobaric/sea level or P_B 1013.25 hPa/760 mmHg), the boiling temperature decreases exponentially with ambient pressure. In humans, without an appropriate pressure suit, the normal body temperature would already be sufficient to bring body fluids to the boil or cause them to evaporate under the stratospheric hypobaria at an altitude of 19,000 m (Armstrong line).

At the most extreme terrestrial altitudes, the reduction in boiling point can be up to 25%. However, this does not provide any time advantage for high-altitude mountaineers when preparing meals, as cooking and preparation times for food are also correspondingly prolonged.

3.6 Equivalence Model: Hypobaric and Normobaric Hypoxia

A hypoxic environment means that the inspiratory partial pressure of oxygen (p_iO_2) is reduced either due to a decreased total atmospheric pressure (p_B) (hypobaric hypoxia [HHX]: natural altitude/decompression chamber) or due to a correspondingly reduced O_2 fraction (F_iO_2) at normal p_B (normobaric hypoxia [NHX]: breathing mask, NHX chamber) compared to sea level. Both forms of hypoxia result in an equally reduced $p_iO_2 < 150$ mmHg.

The formula for calculating F_iO_2 is as follows:

$$F_iO_2 = 0.2093 \times \left(p_{B\,\text{target altitude}} - p_{H2O}\right) \times \left(p_{B\,\text{actual altitude}} - p_{H2O}\right)^{-1}$$

Selected destinations with corresponding F_iO_2 values (hypoxia equivalents) under normobaric conditions, based on the altitude of Graz, Austria, can be found in ▣ Table 3.6.

In principle, the organism responds in a relatively stereotypical manner to hypoxia, regardless of whether hypobaric or normobaric hypoxia is present (HHX/NHX) (Domej et al. 2012). Any reduction in atmospheric pressure (p_B) or p_iO_2, resulting in an equally reduced F_iO_2, has the potential to elicit identical physiological responses and functional adaptations (Millet et al. 2012). Accordingly, HHX and NHX would be largely comparable (equivalence model) (Conkin and Wessel 2008; Self et al. 2011).

However, on closer examination, differences can be found, some of which remain under discussion (Mounier and Brugniaux 2012). There is increasing evidence that different p_B at identical p_iO_2 may induce different responses. As is often the case, a common problem in altitude medicine emerges: com-

▣ **Table 3.6** Selected destinations with corresponding F_iO_2 values

Destination	**p_B (hPa)**	**p_B (mmHg)**	**p_iO_2 (mmHg)**	**F_iO_2 (%)**
Graz, 383 m	970.0	727.7	152.8	0.21
Schöckl, 1445 m	859.2	644.8	135.4	0.18
Dachstein Hunerkogel, 2687 m	742.8	557.3	117.0	0.15
Dachstein summit, 2995 m	Großvenediger, 3662 m	660.5	495.5	104.1
Großglockner, 3761 m	652.5	489.5	102.8	0.13
Matterhorn, 4478 m	613.8	460.2	96.6	0.13
Mont Blanc, 4810 m	577.5	433.2	91.0	0.12
Elbrus, 5642 m	515.5	386.9	81.2	0.10
Mount Everest, 8848 m	336.8	252.7	53.1	0.06
Air travel: minimum permitted cabin pressure ≤8000 ft/2438 m	755.0	580.2	121.8	0.16

p_B total atmospheric pressure, *p_iO_2* inspiratory oxygen partial pressure

parisons based on the available data are often not very meaningful due to differing study methodologies and frequent lack of quality control (Degache et al. 2012; Savourey et al. 2003).

Nevertheless, there is growing evidence of moderate differences between HHX and NHX exposure, particularly with regard to ventilatory aspects, fluid balance, and NO metabolism, but also in terms of the benefit of improved endurance performance and even the prevention of acute mountain sickness (AMS). It therefore seems likely that the equivalence model only applies to approximate isohypoxia between HHX and NHX, as p_B in particular appears to have an independent effect on hypoxia and AMS (Loeppky et al. 1997). In this context, the effectiveness of HHX exposure in achieving sustained pre-acclimatisation compared to a NHX environment may also be somewhat greater, as HHX-imposed hypoxic stress should simulate the effects of natural altitude on the *whole organism more* precisely (Treml et al. 2020).

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Physiological Responses to Altitude

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4.1 Ventilatory Responses to Hypoxia

4.1.1 Control of Breathing

Breathing is regulated by the respiratory centres in the brainstem and modulated by central chemoreceptors in the medulla oblongata as well as by peripheral chemoreceptors in the carotid and aortic bodies (■ Fig. 4.1). At sea level, central chemoreceptors contribute approximately two thirds to respiratory drive, while peripheral chemoreceptors account for about one third (Berger and Luks 2023; Fatemian et al. 2003).

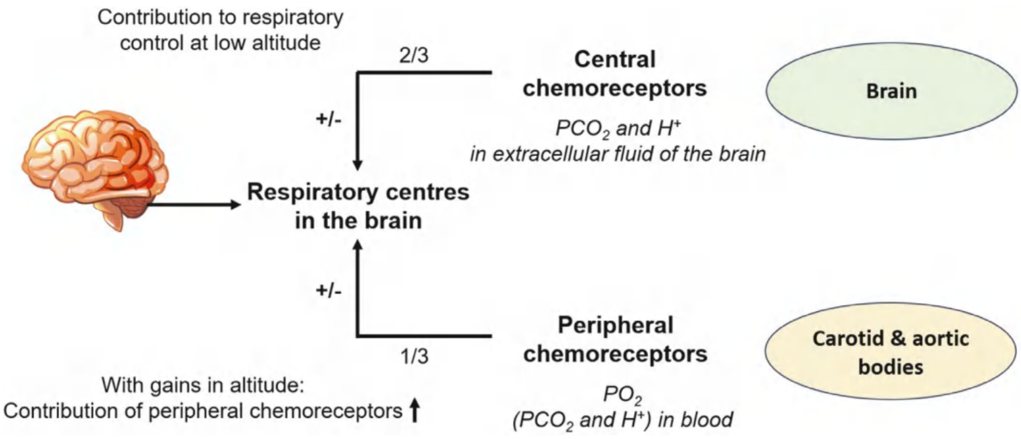
Central chemoreceptors respond to changes in partial pressure of CO_2 (PCO_2) and H^+ ion concentration in the extracellular fluid of the brain. As the blood-brain barrier is highly permeable to dissolved CO_2, an increase in arterial PCO_2 ($PaCO_2$) raises the H^+ ion concentration in the cerebrospinal fluid, leading to an increase in minute ventilation. In contrast, peripheral chemoreceptors primarily respond to changes in arterial oxygen partial pressure (PaO_2), but also to a lesser extent to changes in $PaCO_2$ and arterial H^+ ion concentration (Berger and Luks 2023).

> With increasing altitude, the contribution of peripheral chemoreceptors to the modulation of breathing increases until hypoxaemia, detected in the peripheral chemoreceptors, becomes the driving stimulus to respiratory drive (Powell et al. 1998). Thus, the contribution of central chemoreceptors correspondingly decreases with increasing altitude.

Among the peripheral chemoreceptors, the carotid bodies are a stronger regulator of the hypoxic ventilatory response (HVR) than the aortic bodies (Berger and Luks 2023; Powell et al. 1998).

4.1.2 Ventilation at Altitude

The initial, and most important, physiological response to high altitude is an increase in minute ventilation. Up to certain limits and depending on the absolute altitude, this ensures the maintenance of an adequate alveolar partial pressure of oxygen (PAO_2). The increase in ventilation occurs even at moderate altitude, with a marked rise detectable from around 3000 m (inspiratory PO_2 = approx. 100 mmHg) or a PaO_2 below approx. 60 mmHg (Luks et al. 2021). During acute exposure to altitude, ventilation rises rapidly


Contribution to respiratory control at low altitude
2/3
+/-
Central chemoreceptors
PCO_2 and H^+ in extracellular fluid of the brain
Brain
Respiratory centres in the brain
+/-
1/3
Peripheral chemoreceptors
PO_2 (PCO_2 and H^+) in blood
Carotid & aortic bodies
With gains in altitude:
Contribution of peripheral chemoreceptors ↑

■ **Fig. 4.1** Regulation of breathing. (For details, see text)

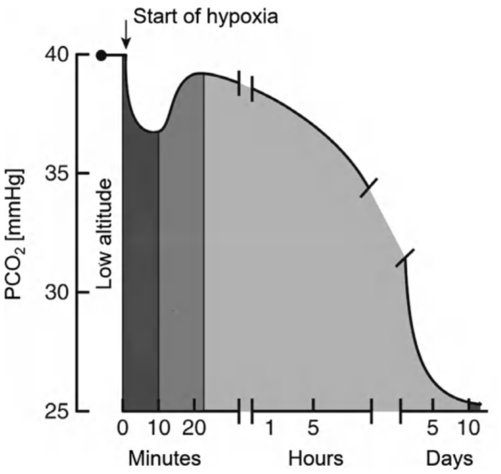


Fig. 4.2 Time course of the hypoxic ventilatory response (HVR). The acute rise in ventilation leads to a decrease in PCO_2, followed by a transient increase in PCO_2 due to hypoxic ventilatory depression (roll-off phenomenon). After about 20 min of acclimatisation, ventilation increases again, resulting in a sustained reduction in PCO_2. (Modified from Berger and Luks 2023; after Smith et al. 2001)

(within minutes), followed by a secondary, transient decline known as the "roll-off phenomenon". After 30–60 min, ventilation increases again and, depending on the absolute altitude and species, reaches a maximum after hours to days, weeks, or even months (Fig. 4.2) (Pamenter and Powell 2016). The extent of the hypoxia-induced ventilatory increase (i.e. the HVR) varies greatly between individuals (Berger and Luks 2023).

Hyperventilation is crucial for maintaining PAO_2, especially at extreme altitudes. Only through an appropriate increase in ventilation and the associated reduction in the alveolar partial pressure of CO_2 ($PACO_2$) can a person at extreme altitude maintain PAO_2 and PaO_2 at levels necessary for survival (Berger and Luks 2023).

Simultaneously with the hyperventilation-induced increase in PAO_2 and PaO_2, the arterial CO_2 partial pressure ($PaCO_2$) decreases, leading to a respiratory alkalosis. This in turn reduces the ventilatory drive mediated by central and peripheral chemoreceptors (as a negative feedback mechanism) (Berger and Luks 2023). During ascent to extreme altitudes and after a period of acclimatisation, extreme degrees of hyperventilation (minute ventilation up to approx. 180 L/min) and respiratory alkalosis can be observed. During an ascent of Mount Everest, at an altitude of 8400 m, a mean $PaCO_2$ value of 13.3 mmHg (10.3–15.7 mmHg) and a pH value of >7.5 were recorded (Grocott et al. 2009).

4.1.3 Hypoxic and Hypercapnic Ventilatory Responses

As described in ▶ Sect. 4.1.2, the extent of altitude-induced hyperventilation is determined by the hypoxic ventilatory response (HVR). This, in turn, is largely dependent on the sensitivity of the peripheral chemoreceptors to changes in PaO_2. The HVR is therefore a measure of how strongly ventilation changes in response to alterations in arterial PO_2 (Berger and Luks 2023).

Various methods are used to measure the magnitude of the HVR. In the rebreathing method, oxygen is consumed from a closed circuit, thereby inducing progressive hypoxaemia. At the same time, peripheral SpO_2 and ventilation are continuously measured. In the steady-state method, a defined oxygen supply (typically between 10 and 14% O_2) is administered, and ventilation and peripheral SpO_2 are measured at the beginning and after 10–15 min of hypoxic exposure. Both methods allow for the assessment of changes in minute ventilation in relation to changes in SpO_2, thereby enabling quantification of the HVR. If inspiratory CO_2 is kept constant during HVR measurement, this is referred to as isocapnic HVR, which primarily determines the ventilatory drive mediated by peripheral chemoreceptors. If CO_2 is not kept constant, poikilocapnic HVR is measured, which results from the combined action of peripheral and central chemoreceptors.

The extent of HVR varies greatly between individuals. For isocapnic HVR, values between 0.51 and 3.10 L/min/%SpO_2 have been reported (Milledge et al. 1991). Women appear to have a lower HVR compared to men (Weil 2003), and older individuals also exhibit a lower HVR compared to a younger population (Sharma and Goodwin 2006).

❯ With acclimatisation from a prolonged stay at altitude, the sensitivity of the peripheral chemoreceptors increases, resulting in a further rise in ventilation at a given, constant altitude (Sato et al. 1992). After returning to sea level, the elevated HVR persists for several days or weeks, so if the individual ascends to high altitude again during this time, the previous ventilatory acclimatisation will be activated (Subudhi et al. 2014).

The pronounced HVR improves oxygen uptake and thus may help preserve physical performance at extreme altitude. This is demonstrated by the fact that only individuals with a strong HVR can tolerate exposure to such altitudes without supplemental oxygen. However, an extremely pronounced HVR may be disadvantageous at altitudes >8000 m (Bernardi et al. 2006), as individuals with a very strong HVR may reach their ventilatory limit at lower altitudes, leaving no ventilatory reserve for even higher elevations. In contrast, individuals with a strong but not extreme HVR are likely to be able to maintain a high minute ventilation at high altitude over extended periods while retaining an adequate ventilatory reserve for the summit. This is particularly the case if a comparable level of ventilation is accompanied by higher ventilatory efficiency (Bernardi et al. 2006).

During prolonged stays at altitude, not only does the sensitivity of the peripheral chemoreceptors to oxygen increase but the sensitivity of the central chemoreceptors to CO_2 also rises (Forster et al. 1971). As a result, ventilation at altitude increases at lower PCO_2 values than would be the case at sea level. The increased CO_2 sensitivity of the central chemoreceptors is partly due to enhanced renal excretion of bicarbonate (HCO_3), which reduces the buffering capacity in the brain's extracellular fluid (Schoene et al. 1990). Consequently, at a given PCO_2 value, stimulation of the central chemoreceptors by H^+ ions is increased (Ainslie et al. 2013). In other words, the increased sensitivity of the central chemoreceptors with progressive acclimatisation leads to a steeper and left-shifted *ventilation-*CO_2 *response curve* (◘ Fig. 4.3).

4.1.4 Gas Exchange

Due to the decrease in PAO_2 at high altitude, the pressure gradient for the diffusion of oxygen from the alveolar space into the capillaries (alveolar-arterial pressure difference, $AaDO_2$) is also reduced. As a result, more time is required for equilibration of PO_2 between these two compartments. This "diffusion limitation" for oxygen is further exacerbated during physical exertion. The increase in cardiac output during exercise shortens the capillary transit time of red

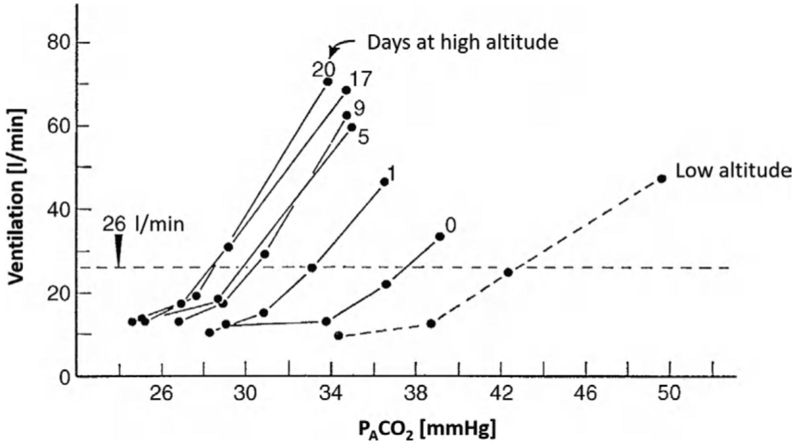


Fig. 4.3 Effect of acclimatisation on the hypercapnic ventilatory response at 4340 m altitude. P_ACO_2 alveolar CO_2 partial pressure; *VE* minute ventilation. (Modified from Berger and Luks 2023; after Pace 1961)

blood cells, making complete equilibration of PO_2 between the alveolar space and capillary blood even more difficult. The result is an increased difference between alveolar and capillary PO_2 and a rise in hypoxaemia (Berger and Luks 2023). At extreme altitudes, diffusion limitation may also occur at rest due to the low pressure gradient and diffusion rate (West and Wagner 1980).

Another important feature of pulmonary gas exchange at high altitude, especially during physical activity, is the deterioration of the physiological ventilation-perfusion ratio, i.e. the relationship between pulmonary ventilation and perfusion (Wagner et al. 1987).

The mechanism underlying the increase in ventilation-perfusion mismatch is not fully understood. Possible causes include the development of subclinical interstitial pulmonary oedema, particularly promoted by the increased cardiac output during exercise on ascent, as well as by uneven hypoxic pulmonary vasoconstriction (HPV) with regional over-perfusion of certain lung regions. An increased shunt due to a patent foramen ovale, present in approximately 30% of the population, and/or an increased right-to-left shunt due to intrapulmonary arteriovenous anastomoses may also contribute to ventilation-perfusion mismatch (Berger and Luks 2023).

4.1.5 Lung Mechanics and Dynamics

Lung mechanics change at altitude with vital capacity have been well studied. Although some studies show no effect of altitude, it appears that vital capacity is impaired during acute and subacute exposure to high altitude (Berger and Luks 2023). The decrease may be caused by the accumulation of interstitial fluid, reduced respiratory muscle strength, hypocapnia, and/or increased pulmonary blood volume (Deboeck et al. 2005; Mason et al. 2000; Welsh et al. 1993). Results on static lung compliance are controversial; some studies report a decrease, some an increase, and others no change in this parameter at altitudes between 3000 and 4559 m (Gautier et al. 1982; Jaeger et al. 1979; Raymond and Severinghaus 1971).

Due to the increased ventilation at high altitude, the question arises as to whether early fatigue of the respiratory muscles occurs. At rest, the results on respiratory muscle strength are inconsistent. However, studies conducted during physical exertion indicate that various markers of respiratory muscle strength, including the ability to generate force, time to exhaustion, and time to diaphragmatic recovery, are impaired at high altitude (Gudjonsdottir et al. 2001). The clinical significance of these changes remains unclear.

Changes in airway resistance at altitude are also inconsistent. Some studies have reported a decrease in resistance, while others have found no change (Dehnert et al. 2010; Gautier et al. 1982). This may be due to the simultaneous interaction of several opposing factors. On the one hand, hypocapnia may increase airway resistance, while on the other hand, a decrease in air density or increased activity of the sympathetic nervous system may reduce airway resistance. However, with increasing altitude, the lower air density appears to increase peak expiratory flow rate (Berger and Luks 2023; Mason et al. 2000).

4.1.6 Pulmonary Vascular Adaptation

Alveolar hypoxia leads, via the Euler-Liljestrand mechanism, to constriction of the pulmonary arterioles (hypoxic pulmonary vasoconstriction, HPV) (Berger and Luks 2023). This results in the diversion of blood flow from poorly ventilated to well-ventilated regions of the lung, thereby optimising alveolar gas exchange. In situations where alveolar hypoxia occurs only locally, such as in patients with pneumonia, this mechanism is advantageous (Berger and Luks 2023). At altitude, where alveolar hypoxia is present throughout the entire lung rather than locally, HPV no longer serves a physiological purpose. Instead, it leads to an increase in pulmonary vascular resistance and, consequently, pulmonary arterial pressure. In particular, when combined with an increase in cardiac output at altitude (see ▶ Sect. 4.2), right ventricular afterload is elevated (Berger and Luks 2023; Smith et al. 2012).

The extent of HPV is not uniform throughout the lung (Dehnert et al. 2006) and, like the HVR, exhibits considerable variability between individuals. Due to the regional heterogeneity of HPV, some areas of the pulmonary vasculature receive greater perfusion than others.

> In individuals with an exaggerated HPV, this heterogeneity may contribute to the development of high-altitude pulmonary oedema, a non-cardiogenic form of pulmonary oedema (see ▶ Chap. 9).

HPV occurs in several phases, with the first beginning within seconds of hypoxic exposure. A second phase begins after approximately 2 h, followed by a further increase in pulmonary vascular pressure over the next 6–8 h (Talbot et al. 2005; Vejlstrup et al. 1997). The mechanisms underlying HPV are complex and originate in the vascular smooth muscle. In the initial phase, hypoxia leads to the formation of free oxygen radicals and other reactive oxygen species, which increase intracellular Ca^{2+} concentration, resulting in contraction of the smooth muscle cells in the pulmonary vessels. In the second phase, vasoconstriction is maintained by a sustained reduction in the bioavailability of nitric oxide in conjunction with an increase in endothelium-derived vasoconstrictors, such as endothelin-1 (Bailey et al. 2010; Berger et al. 2005). These processes are modulated by various factors, including pulmonary innervation, circulating hormones, acid-base status, and erythrocytes.

In cases of short-term hypoxic exposure (hours to a few days), HPV can be completely reversed by the administration of oxygen (Subedi et al. 2023). With prolonged hypoxia, however, vascular remodelling occurs, leading to structural changes in the pulmonary vasculature and a progressive reduction in the reversibility of HPV by supplemental oxygen (Berger and Bailey 2023). Vascular remodelling is the result of a multistep process in which hypoxia-inducible factor (HIF) 1-α is considered the principal mediator (Shimoda and Laurie 2014). Hyperproliferation of endothelial cells, smooth muscle cells, and fibroblasts, as well as accumulation of extracellular matrix (i.e. the entirety of all macromolecules in the intercellular space), lead to thickening of the vessel wall and stiffening of the vessels (Shimoda 2020). The precise time course of remodelling and the attenuated response to supplemental oxygen is not known but likely begins within a few days to weeks (Subedi et al. 2023).

4.2 Cardiocirculatory and Systemic Responses to Hypoxia

Maintaining oxygen supply at high altitude depends not only on gas exchange and an adequate arterial oxygen content in the blood but also on the ability to deliver oxygen-rich blood to the tissues. The peripheral chemoreceptors are the primary sensors that detect the hypoxaemic stimulus during altitude exposure. This not only triggers immediate hyperventilation but also induces acute cardiovascular responses, followed by subsequent adaptation.

4.2.1 Cardiovascular Regulation at Altitude Under Resting Conditions

During acute exposure to altitude, sympathetic activation and reduced parasympathetic activity lead to an increase in resting heart rate (tachycardia) (Berger and Luks 2023). The extent of these changes is proportional to the degree of hypoxia. In contrast to heart rate, stroke volume does not change significantly (Williams et al. 2022). Overall, this results in an increased cardiac output, which maintains convective oxygen transport in the face of reduced arterial oxygen content. Additionally, in peripheral vessels (in contrast to pulmonary vessels), the hypoxic stimulus induces vasodilation, which counteracts the sympathetically mediated vasoconstriction (Baggish et al. 2014). This ensures that peripheral tissues receive the required amounts of oxygen and nutrients. The interplay between sympathetic vasoconstriction and hypoxic vasodilation also affects blood pressure regulation. Blood pressure measured during the first hours of acute high-altitude exposure appears to be slightly reduced due to vasodilation and decreased peripheral vascular resistance (Baggish et al. 2014). However, when blood pressure is measured after several hours at high altitude, sympathetic vasoconstriction tends to result in an increase in blood pressure (Wolfel et al. 1994). The magnitude of these changes, however, depends greatly on the absolute altitude.

With prolonged stay at high altitude, resting heart rate decreases again, but remains elevated compared to sea level, especially at altitudes above 3000 m (Baggish et al. 2014; Richalet et al. 2023). The persistently elevated heart rate over the longer term appears to be due to a reduction in parasympathetic activity and less to sympathetic influence, as acclimatisation is associated with a decrease in β-receptor density (downregulation) (Siebenmann et al. 2017a). In contrast, stroke volume tends to decrease during altitude exposure. This is largely attributable to a reduction in plasma volume as a result of the diuretic response to hypoxia and/or fluid shifts due to changes in oncotic pressure (loss of plasma proteins) (Roche et al. 2022; Schlittler et al. 2021; Siebenmann et al. 2013). In addition, stroke volume may be reduced by a decreased end-diastolic volume caused by increased pulmonary arterial pressure (Richalet et al. 2023). As acclimatisation to high altitude over time also leads to an increase in haemoglobin mass and oxygen transport capacity, cardiac output subsequently returns to sea-level values or may even be slightly reduced (Luks et al. 2021). It should also be noted that there is no evidence that cardiac function in healthy individuals is negatively affected by high altitude in any way (Baggish et al. 2014). This was impressively demonstrated during the Operation Everest II expedition, where at all altitudes (up to over 8000 m) end-systolic volume was reduced compared to sea level, and all indices of left ventricular systolic function were unchanged or even increased (Suarez et al. 1987). It has also been shown that clinically significant arrhythmias, for example, those triggered by myocardial ischaemia, are rare even at extreme altitudes (around 8000 m), where PaO_2 values may be as low as 30–35 mmHg (Grocott et al. 2009). This is probably because hypoxaemia induces coronary vasodilation, thereby maintaining adequate myocardial perfusion and oxygen supply (Wyss et al. 2003).

During prolonged high-altitude exposure, sympathetic activation increases continuously (Hansen and Sander 2003). In addition, haematological adaptations restore arterial oxygen content, thus reducing local vasodilation. These changes lead, with individual variation, to an increase in blood pressure (Baggish et al. 2014). If the stay at high altitude is further prolonged, for example, for more than 90 days above 3000 m, a reduction in sympathetic activity may occur, as evidenced by a decrease in catecholamine concentration (Sharma et al. 1978). As a result, blood pressure may also normalise (Baggish et al. 2014).

4.2.2 Cardiovascular Regulation at Altitude During Exercise

During moderate exercise, at high altitude, as with the resting condition, heart rate is acutely increased compared to equivalent exercise at sea level, while stroke volume remains unchanged (Baggish et al. 2014). This results in an increase in cardiac output at a given absolute workload (e.g. 150 W when cycling or running at 8 km/h). After an acclimatisation phase, heart rate remains slightly elevated, while stroke volume and cardiac output decrease (Baggish et al. 2014). These changes are related to adaptation processes in other systems (such as increased ventilation and haematological adaptations). In this context, peripheral blood flow during exercise is regulated locally according to demand: During acute altitude exposure, the reduced arterial oxygen content is compensated by increased blood flow, whereas after ventilatory and haematological adaptations (i.e. increased arterial oxygen content), blood flow can be reduced while still maintaining oxygen delivery (Baggish et al. 2014). Local vasodilation appears to be mediated, among other factors, by adenosine, nitric oxide, and ATP released from deoxygenated erythrocytes (Dietrich et al. 2000; Marshall 2015).

During maximal exercise, heart rate is initially slightly reduced and decreases significantly with prolonged (>24 h) exposure at altitude. Here, too, downregulation of β-receptors appears to be the explanatory factor (Richalet et al. 2023). Maximal stroke volume and cardiac output are initially maintained during acute hypoxia but also decrease during acclimatisation (Baggish et al. 2014). Maximal exercise capacity (maximal oxygen uptake, VO_2max) is therefore reduced both acutely and after acclimatisation, with the decrease during acute exposure being mainly explained by the reduced arterial oxygen content, while with prolonged stay, the reduced maximal cardiac output becomes more significant (Baggish et al. 2014). Redistribution of blood to inactive tissues is discussed as an additional cause for the persistent reduction in VO_2max (Calbet et al. 2003). In general, in moderately trained individuals, VO_2max decreases by approximately 5–10% per 1000 m gain in altitude from 1500 m upwards (Buskirk et al. 1967). In endurance athletes, the decrease begins from an altitude of 800 m (Wehrlin and Hallen 2006).

4.3 Haematological Adjustments to Hypoxia

Beyond ventilatory and cardiovascular adjustments, the body employs several haematological adjustments to help maintain arterial oxygen content during altitude exposure. Oxygen transport in humans occurs via binding to haemoglobin. Hb-O2 binding is altered by modification of allosteric factors, and the haemoglobin concentration in the blood is increased through plasma volume reduction and erythropoiesis.

4.3.1 The Haemoglobin Molecule

Haemoglobin (Hb) is considered one of the best-studied proteins in the human body. To efficiently and reliably perform its main function—oxygen transport—it depends on a certain quantity and several specific characteristics, which are presented in this section. The primary role of haemoglobin in vertebrates is the transport of oxygen for aerobic cellular metabolism (Mairbaurl and Weber 2012). In addition, it is involved in other important functions, such as catalytic processes (nitrite reductase, NO-dioxygenase, monooxygenase, alkyl hydroperoxidase, esterase, lipoxygenase), nitric oxide metabolism, pH regulation, and maintenance of redox balance (Kosmachevskaya and Topunov 2018).

Haemoglobin was first described in 1840 by Friedrich Ludwig Hünefeld. In 1878, Paul Bert reported on the binding of O_2 to Hb, and more than 100 years ago, Christian Bohr identified the first characteristics of Hb oxygen uptake and release. The phenomenon whereby a decreased pH reduces Hb-O_2 affinity is named after him (Bohr effect). In the following years, Haldane and colleagues demonstrated the effect of CO_2 on Hb-O_2 binding, as well as the reciprocal effect of O_2 on Hb-CO_2 binding (Haldane effect) (Christiansen et al. 1914). Hans Fischer was awarded the Nobel Prize in Chemistry in 1930 for the synthesis of haemin. Max Perutz subsequently received the Nobel Prize in Chemistry in 1962 for the structural analysis of Hb by X-ray crystallography (Ahmed et al. 2020).

4.3.1.1 Structure

Hb is a tetrameric molecule with a molecular weight of approximately 64,500 daltons. Adult Hb consists predominantly of two α and two β chains (HbA_1). Each of these subunits contains a haem group, which possesses a central iron atom (Fe^{2+}) essential for O_2 binding. Thus, a single Hb molecule can bind up to four O_2 molecules. As in other mammals, several different Hb subunits are present in humans. Starting with Hb Gower ($\zeta_2\varepsilon_2$ or $\alpha_2\varepsilon_2$) and Hb Portland ($\zeta_2\gamma_2$ or $\zeta_2\beta_2$) in early embryonic development, oxygen transport in the foetus occurs mainly via foetal Hb (HbF $\alpha_2\gamma_2$). HbF is characterised by increased Hb-O_2 affinity, enabling efficient placental oxygen transfer from maternal to foetal Hb. While HbF may still be present in trace amounts in adults, HbA (or HbA_1 $\alpha_2\beta_2$) is by far the most common variant, whereas HbA_2 ($\alpha_2\delta_2$) is present only in a small percentage. Pathological Hb subunits are discussed later in this chapter. Post-translational modifications are common, such as glycosylation of Hb leading to HbA_{1c}, an important marker for monitoring diabetes mellitus, but acetylation, methylation, and nitrosylation also occur (Mairbaurl and Weber 2012).

4.3.1.2 Oxygen Transport

As described above, each of the four Hb subunits contains a haem group with a central iron atom, which is essential for O_2 binding. Upon O_2 binding, the position of the iron atom within the haem group changes. The tertiary structure of the Hb subunit is altered, thereby facilitating O_2 binding to the next subunit, a phenomenon known as positive cooperativity. When an Hb molecule is fully oxygenated, its quaternary structure and absorption characteristics change slightly, a property that is exploited in measurement techniques. Positive cooperativity is reciprocal, i.e. O_2 binding to the first Hb subunit promotes further oxygenation of the remaining subunits, and conversely, dissociation of O_2 from the first subunit in oxygenated Hb facilitates deoxygenation of the entire Hb molecule.

The term *oxygen delivery* (DO_2) refers to the amount of O_2 that is “delivered” to the tissue via the blood within a given period. DO_2 is the product of cardiac output and arterial oxygen content (CaO_2). Cardiac output itself is the product of stroke volume (SV) and heart rate (HR), while CaO_2 includes both haemoglobin-bound and physically dissolved O_2. One gram of haemoglobin can bind a maximum of 1.34 ml O_2 (Hüfner number). Thus, the following formula applies for DO_2:

$$DO_2 = SV \times HR \times \left(1.34 \times [Hb] \times SaO_2 + 0.003 \times paO_2\right)$$

Here, [Hb] denotes the haemoglobin concentration.

Oxygen consumption (oxygen uptake, VO_2) in turn indicates the amount of O_2 that is “consumed” by the tissue within a given period. VO_2 can be measured and calculated in several ways. By subtracting the venous oxygen content from the arterial and multiplying by the cardiac output, oxygen consumption is obtained:

$$VO_2 = \text{Cardiac Output} \times \left(CaO_2 - CvO_2\right)$$

VO_2max, the maximum oxygen consumption achievable by an individual, is an important parameter in exercise physiology.

These formulae show that, in addition to cardiocirculatory parameters, haemoglobin concentration and oxygen saturation are key factors determining oxygen transport. The Hüfner number cannot be influenced. Haemoglobin concentration and oxygen saturation, on the other hand, are regulated by numerous mediators and processes and are adapted to prevailing environmental conditions, including altitude. Oxygen consumption is determined not only by supply but also by extraction. The more O_2 released to the tissue, the more O_2 is available for the tissue to utilise. The oxygen extraction rate (O_2ER) is calculated from CaO_2 and CvO_2:

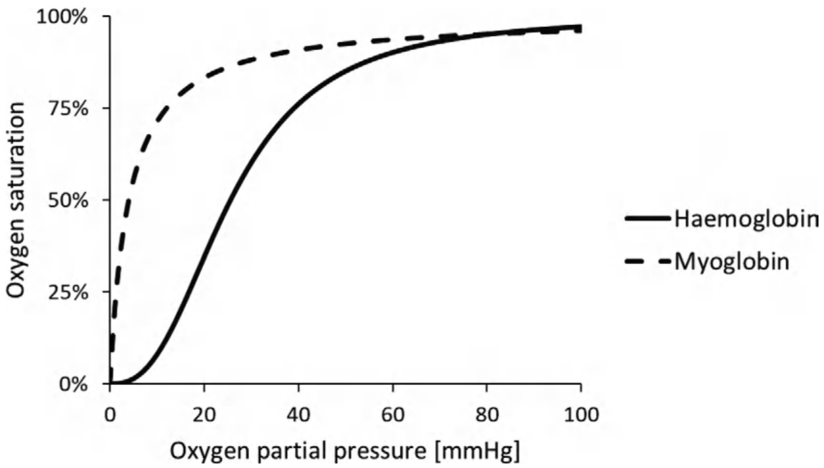
$$O_2ER = \left(CaO_2 - CvO_2\right) / CaO_2$$

The Hb-O_2 affinity determines the O_2ER.

Many of the topics discussed in this chapter revolve around various regulatory processes aimed at maintaining oxygen delivery at altitude.

4.3.1.3 The Myoglobin Molecule

Unlike Hb, myoglobin is a monomeric globin. Myoglobin also contains one haem group with a central iron atom and is



◘ **Fig. 4.4** Oxygen dissociation curves of haemoglobin (sigmoidal) and myoglobin (hyperbolic). Schematic representation

responsible for oxygen transport and supply within muscle, i.e. in the myocardium and skeletal muscle. Its binding kinetics differ significantly from those of Hb; myoglobin has a very high oxygen affinity (◘ Fig. 4.4) and, unlike Hb, is not influenced by various allosteric factors.

4.3.1.4 Pathological Haemoglobin Variants

Carbon monoxide (CO) competes with oxygen for binding to the central iron atom of the haem group in haemoglobin (Hb), with CO exhibiting approximately 200 times greater affinity than oxygen. When CO binds to Hb, carboxyhaemoglobin (COHb) is formed. COHb is characterised by a markedly increased affinity of the remaining binding sites of the other Hb subunits for O_2. At low concentrations, COHb is also present in healthy individuals. In cases of CO poisoning, for example, from smoke inhalation, COHb can reach life-threatening concentrations. Elevated COHb levels lead to a reduction in oxygen transport capacity, as COHb, due to its higher Hb-CO affinity, cannot participate in oxygen transport (Mairbaurl and Weber 2012).

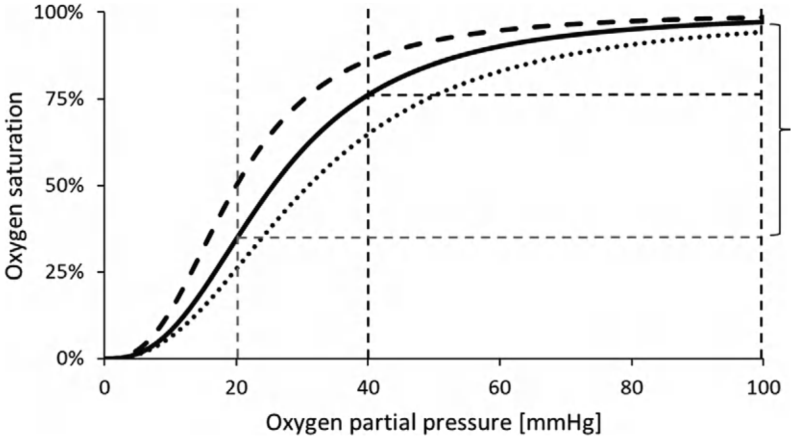
If the central iron atom of the haem group is oxidised ($Fe^{2+} \rightarrow Fe^{3+}$), methaemoglobin (MetHb) is formed. Normally, MetHb is present only at low concentrations, as methaemoglobin reductase reduces the iron atom and maintains MetHb concentration within physiological limits. MetHb cannot bind oxygen; instead, it binds water and therefore cannot participate in oxygen transport, resulting in a reduced oxygen transport capacity.

Rare genetic haemoglobinopathies can lead to a markedly increased or decreased Hb-O_2 affinity. In a recent study, individuals with a high-oxygen-affinity haemoglobinopathy (p50 = 16 mmHg) were compared with healthy controls (p50 = 26 mmHg). Exercise tests were conducted under normoxic and hypoxic conditions (F_iO_2 15%, ~3000 m). Individuals with high-oxygen-affinity haemoglobinopathy exhibited higher SpO_2 values under hypoxia, and the decrease in VO_2max was less pronounced than in the control group. This suggests that a leftward shift of the oxygen dissociation curve may have beneficial effects on hypoxia adaptation, even in individuals with normal Hb (Dominelli et al. 2020).

The specific binding properties of haemoglobin and oxygen enable efficient oxygen transport. Arterial oxygen content is essentially determined by haemoglobin concentration, the prevailing pO2 in the pulmonary capillaries and haemoglobin-oxygen binding.

4.3.2 Oxygen Dissociation Curve

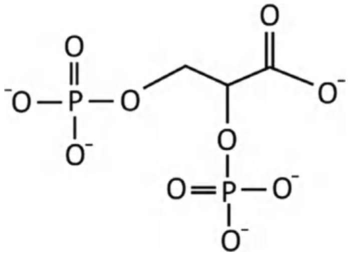
The oxygen dissociation curve (ODC) (◘ Fig. 4.5) describes the unique binding kinetics of oxygen to haemoglobin, which are crucial for efficient oxygen transport from the pulmonary capillaries to oxygen-consuming tissues (Imai 1982; Mairbaurl and Weber 2012). Hb-O_2 binding is primarily influenced by four allosteric fa ctors: pH, temperature, pCO_2, and 2,3-bisphosphoglycerate (2,3-BPG) (Mairbaurl and Weber 2012). A decreased pH or increased H^+ ion concentration lead to a reduced Hb-O_2 affinity and thus to a rightward shift of the ODC. Similarly, increased temperature, elevated pCO_2, and higher 2,3-BPG concentrations have the same effect. Conversely, a decrease in H^+ ion concentration, lower temperature, reduced pCO_2, and decreased 2,3-BPG concentration increase Hb-O_2 affinity, resulting in a leftward shift of the ODC. A leftward shift of the ODC is associated with improved oxygen uptake in the pulmonary capillaries, whereas oxygen release to the tissues may be limited. In contrast, a rightward shift of the ODC may impair oxygen uptake in the lungs but enhance oxygen delivery to the tissues. In addition to these four main effectors, numerous other parameters can influence Hb-O_2 affinity, either directly by binding to the haemoglobin molecule and modifying its structure—thereby stabilising either the oxygenated (“relaxed state”) or deoxygenated (“tense state”) form—or indirectly by altering one of the main effectors of the ODC mentioned above. The oxygen dissociation curve is characterised by a sigmoidal shape, which is due to the positive cooperativity of Hb-O_2 binding. Essentially, the ODC is characterised by two parameters: The p50 is the pO_2 at which 50% of haemoglobin is saturated with oxygen and serves as an indicator for a leftward or right-



◘ **Fig. 4.5** Oxygen dissociation curve: normal (*black curve*), left-shifted (*black dashed curve*), and right-shifted (*black dotted curve*). The vertical dashed line on the right indicates the partial pressure of oxygen in the pulmonary capillaries (right), while the two dashed lines on the left indicate the partial pressure of oxygen at the tissue level (*black dashed line* for 40 mmHg and *grey dashed line* for 20 mmHg). The *bracket* indicates the amount of oxygen that can be released to the tissue if the tissue pO_2 is 20 mmHg ward shift of the ODC. The Hill coefficient describes the steepest slope in the Hill plot, a double-logarithmic representation of the ODC, and is a parameter for the degree of positive cooperativity of Hb-O_2 binding. Under certain conditions, such as hypoxia at high altitude, during physical exertion, or in hypoxaemia due to pulmonary disease with diffusion limitation, it is currently debated whether an increased or decreased Hb-O_2 affinity might be advantageous (Dempsey 2020; Shepherd et al. 2019; Woyke et al. 2020).

4.3.2.1 2,3-Bisphosphoglycerate

2,3-BPG (◘ Fig. 4.6) is produced via the Rapoport-Luebering pathway, a bypass of glycolysis, by bisphosphoglycerate mutase from 1,3-bisphosphoglycerate. Subsequently, 2,3-BPG can be metabolised to 3-phosphoglycerate by bisphosphoglycerate phosphatase. The Rapoport-Luebering shunt of glycolysis yields one less ATP than regular glycolysis, thus costing one ATP. The formation of 2,3-BPG, i.e. the activity of 1,3-bisphosphoglycerate mutase, is determined primarily by pH, in addition to other regulatory processes. 2,3-BPG is one of the main factors influencing the ODC. Every mammal possesses an organic phosphate compound within erythrocytes; in humans, this is 2,3-BPG, but this is not universal. Without 2,3-BPG or a similar molecule, the Hb-O_2 affinity would be so high that the binding kinetics would resemble those of myoglobin. Adequate oxygen transport is therefore inconceivable without 2,3-BPG.



◘ Fig. 4.6 2,3-bisphosphoglycerate structural formula

4.3.2.2 The Oxygen Dissociation Curve at Altitude

At moderate and high altitudes, the onset of hyperventilation leads to hypocapnia and altitude alkalosis, a respiratory alkalosis. Driven by alkalosis and other mediators, there is, over the course of hours or days, an increase in 2,3-BPG, which counteracts this initial increase in Hb-O_2 affinity. Accordingly, at 1700 m, a leftward shift of the ODC compared to sea level was observed due to respiratory alkalosis, while 2,3-BPG increased only after a delay of several days (Humpeler et al. 1979). In another study at 2300 m, the increase in p50 was associated with a simultaneous rise in 2,3-BPG (Mairbäurl et al. 1986). At 4500 m, however, under standard conditions (pCO_2 = 40 mmHg), an increase in p50 was observed, while under natural conditions (alkalosis), p50 did not change. An increase in 2,3-BPG was noted within 1 day (Mairbäurl et al. 1990), with a plateau expected only by day 4 (Mairbäurl et al. 1993). In contrast, p50 reaches a plateau as early as the first day (at 4500 m) (Mairbäurl et al. 1993). In addition to 2,3-BPG, chloride, cellular haemoglobin concentration, and magnesium also contribute within a short time to a rightward shift of the ODC (Mairbäurl et al. 1993). In contrast to these studies, Balaban and colleagues were able to demonstrate a leftward shift of the ODC when subjects were exposed to an altitude of 4000 m, without measuring 2,3-BPG (Balaban et al. 2013). In summary, it can be stated that at high altitudes, there is an increase in 2,3-BPG, which, when the ODC is measured under standard conditions, leads to a rightward shift. In vivo, however, respiratory alkalosis almost completely counteracts this effect, so that p50 remains within the normal range. The allosteric factors that determine Hb-O_2 affinity thus appear to ensure the functionality of Hb-O_2 transport at altitude.

At extreme altitudes, the effect of respiratory alkalosis (hyperventilation) with pronounced hypocapnia (leftward shift) clearly outweighs the effect of increased 2,3-BPG concentration (Wagner et al. 2007; Winslow et al. 1984). The result is a markedly increased Hb-O_2 affinity. This has been demonstrated by comparing the current p50 (pCO_2 and 2,3-BPG effect) with the p50 under standard conditions (2,3-BPG effect only) (Wagner et al. 2007). In such an environment with greatly reduced partial pressures of oxygen, an increased Hb-O_2 affinity could improve pulmonary oxygen uptake and thus enable efficient Hb-O_2 transport.

> The oxygen dissociation curve remains constant at moderate altitudes; an increase in 2,3-BPG counteracts the effect of respiratory alkalosis. At extreme altitudes, the influence of the markedly reduced pCO2 outweighs that of the increased 2,3-BPG concentration, and the oxygen dissociation curve is shifted to the left, i.e. Hb-O2 affinity is increased.

4.3.3 Oxygen Transport Capacity

To counteract a reduction in CaO_2 due to hypoxia and the resulting decrease in SaO_2 and paO_2 at altitude, the concentration of oxygen carriers (Hb) is increased as a compensatory mechanism (Lundby et al. 2004). Haemoconcentration occurs primarily through a reduction in plasma volume; erythropoiesis is simultaneously stimulated and, over the course of weeks, leads to a further increase in Hb through enhanced production of reticulocytes and erythrocytes. The result is an increase in total Hbmass (Siebenmann et al. 2015).

4.3.3.1 Reduction in Plasma Volume

The reduction in plasma volume for the purpose of haemoconcentration occurs within the first 24 h of altitude exposure. The physiology underlying this rapid reduction in plasma volume is currently the subject of intensive research and is likely to be multifactorial. Water loss due to increased diuresis (altitude diuresis) and the associated reduction in total body water and extracellular volume (plasma volume) and/or redistribution of water from the intravascular to the extravascular compartment and/or contraction of the spleen are discussed as possible causes (Siebenmann et al. 2023). Recent studies conducted under standardised altitude conditions point more towards a redistribution from the intravascular to the extravascular compartment (Roche et al. 2022; Schlittler et al. 2021). The diuresis triggered by acute hypoxia appears to be a short-term phenomenon without significant effects on extracellular volume. During altitude sojourns and in field studies, other non-hypoxia-specific factors may play a relevant role. For example, altered drinking behaviour, increased urination, and various environmental influences—especially during ascent to high altitudes—may dominate the effects of hypoxia on diuresis and fluid regulation processes (Siebenmann et al. 2023). The mechanism by which fluid is redistributed from the intravascular to the extravascular compartment has not yet been fully elucidated; hypoxia-induced reduction in total protein concentration in the blood, and thus in colloid osmotic pressure, may play a decisive role (Siebenmann et al. 2023; Young et al. 2019; Roche et al. 2022; Schlittler et al. 2021). Whether proteinuria, capillary leak, increased sympathetic tone, or a reduced rate of protein synthesis in hypoxia is responsible for the observed reduction in total protein remains unclear at present (Siebenmann et al. 2023). The spleen is considered a reservoir for erythrocytes, with the haematocrit in the spleen being significantly higher than that in circulating blood. Triggered by hypoxia, contraction of the spleen can rapidly release additional erythrocytes into the bloodstream. This results in an increase in blood haematocrit, which could lead to an overestimation of the reduction in plasma volume. However, it is assumed that the extent of this effect is minor, as splenic contraction is thought to provide only about 50 ml of erythrocytes to the circulating blood (Siebenmann et al. 2023).

4.3.3.2 Erythropoiesis

Through increased erythropoiesis, that is, the formation of new erythrocytes, the quantity of erythrocytes, and thus the haemoglobin mass, is elevated over the course of several weeks. This enhanced erythropoiesis is primarily due to increased erythropoietin release from the peritubular cells of the kidney. The reduced oxygen supply to the kidney in hypoxia, mainly mediated by HIF-2 ("hypoxia-inducible factor-2"), but also by HIF-1, leads to increased production and release of erythropoietin (Jelkmann 2011). The rise in erythropoietin release occurs within a few hours and peaks after 2 days. Subsequently, increased numbers of reticulocytes, the precursors of erythrocytes, are released from the bone marrow into the circulating blood. The rate at which haemoglobin mass increases depends on the altitude reached (Fig. 4.7) (Rasmussen et al. 2013).

4.3.3.3 Normalisation of Haemoglobin Concentration After Return from High Altitude

Within 1–2 weeks after returning from high altitude, haemoglobin mass normalises. It is assumed that neocytolysis, the breakdown of young erythrocytes, plays a key role as a process counteracting the increased erythropoiesis. More recent studies, however, suggest that reduced production rather than neocytolysis is responsible. The precise mechanism underlying the relatively rapid normalisation of haemoglobin mass therefore remains the subject of current research (Siebenmann et al. 2023).

> Oxygen transport capacity or haemoglobin concentration is initially increased by plasma volume reduction and subsequently by enhanced erythropoiesis. After return from high altitude, these mechanisms regress within a few days.

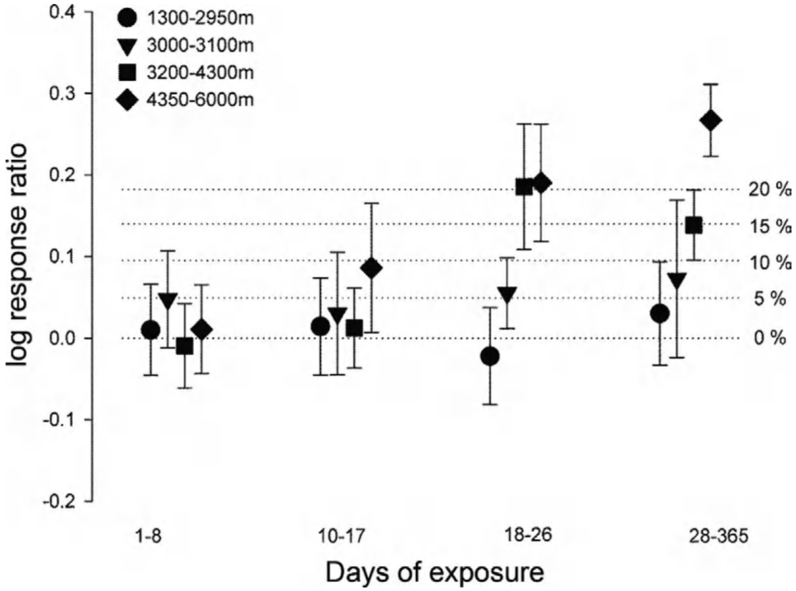


Fig. 4.7 Erythrocyte volume (analogous to haemoglobin mass) at different altitudes. The figure shows the results of a meta-analysis of 66 original studies. The extent and rate of increase in erythrocyte volume depend on altitude. (From Siebenmann et al. 2023, with kind permission)

4.3.4 Genetic Adaptation to High Altitude

In Humans

Highland populations in Tibet or Ethiopia exhibit less pronounced increases in haemoglobin concentration compared to Andean populations and to residents of lowland regions. The hypoxia-induced modulation of plasma volume and haemoglobin mass appears to be less marked in highland populations than in mountaineers from lower altitudes who only occasionally spend time at high altitude. The reasons for this are not yet fully understood (Siebenmann et al. 2023). It is, however, well established that both particularly low and particularly high haematocrit levels have negative effects on microcirculation. There is also evidence that markedly elevated haemoglobin concentrations do not substantially increase VO_2max; the lung's diffusion capacity and the limited diffusion gradient in hypoxia appear to play a key limiting role. As early as 1923, Barcroft investigated the oxygen affinity of Peruvian natives (4300 m) at high altitude and found that their p50 was lower compared to people living at sea level (Barcroft 1923). This has recently been confirmed for Han Chinese and Tibetans (Li et al. 2018). At present, it is generally assumed that the $Hb\text{-}O_2$ affinity of high-altitude residents does not differ significantly from that of inhabitants of lower regions, particularly with regard to their allosteric modifications (Mairbaurl and Weber 2012). Whether and to what extent a leftward shift of the oxygen dissociation curve can provide a long-term benefit at high altitude remains a subject of ongoing research; however, an increased $Hb\text{-}O_2$ affinity could support pulmonary oxygen uptake under hypoxic conditions (Dempsey 2020).

In Animals

Both mammals and birds living at high altitude are adapted to prevailing hypoxia. A notable example is the bar-headed goose, which migrates from China across the Himalayas to its breeding grounds in the Bay of Bengal. Compared to related species from lower altitudes, it exhibits a markedly increased $Hb\text{-}O_2$ affinity. The haemoglobin of the bar-headed goose consists of different subunits compared to its lowland relatives. Through allosteric modification of haemoglobin, particularly due to the high affinity for inositol pentaphosphate, oxygen delivery at the tissue level is also ensured. In the bar-headed goose, both oxygen uptake by haemoglobin in the pulmonary capillaries and oxygen release at the tissue level occur within the steep portion of the oxygen dissociation curve, resulting in efficient oxygen transport (Mairbaurl and Weber 2012). Among mammals, hypoxia-tolerant camelids serve as exemplary species. Differences in the composition of haemoglobin subunits exist among camelids depending on altitude. When haemoglobin from hypoxia-tolerant camelids is isolated, the subunits display even lower $Hb\text{-}O_2$ affinity compared to those from camelids inhabiting lower regions. However, in intact erythrocytes containing 2,3-BPG, this changes dramatically: the haemoglobin subunits of hypoxia-tolerant species lack binding sites for 2,3-BPG, resulting in a significantly increased $Hb\text{-}O_2$ affinity (Mairbaurl and Weber 2012). In summary, it can be stated that hypoxia-tolerant species, whether birds or mammals, exhibit increased $Hb\text{-}O_2$ affinity.

Genetic adaptation to altitude generally occurs via enhanced Hb-O2 binding, resulting in a leftward shift of the oxygen dissociation curve.

4.4 Cerebrovascular Responses to Hypoxia

4.4.1 Cerebral Blood Flow and Cerebral Oxygen Supply in Acute Hypoxia

Depending on the degree of hypoxia exposure, the brain plays a central role in adjusting to reduced arterial oxygen partial pressure. Cerebrovascular responses to altitude must always be considered in close conjunction with other essential adaptive processes (Hoiland et al. 2018). This particularly concerns ventilatory adaptation, i.e. the necessary hyperventilation. Additionally, although the brain accounts for only about 2% of total body mass, its resting O_2 consumption is approximately 20% of total O_2 consumption. Key adaptive mechanisms include afferent feedback from the cardiovascular and respiratory systems, along with their respective control centres in the central nervous system. Furthermore, the altered acid-base status, with hypocapnia and respiratory alkalosis, affects cerebral perfusion during hypoxia. Other influencing factors, especially at high and extreme altitudes, include hypobaria and cold. The potential negative effects of acute and chronic hypoxia on the central nervous system are the subject of considerable debate (Zhang and Zhang 2022).

Hyperventilation and the resulting ventilatory acclimatisation are regarded as the most important adaptive mechanisms, with far-reaching consequences for other systems. While acute hyperventilation mitigates the altitude-induced reduction in PaO_2, ventilatory acclimatisation is responsible for a further, progressive increase in PaO_2 over the duration of high-altitude exposure. Haematological adaptations, such as increases in erythrocyte count or mass, are slow to develop and only occur at a later stage. All the adaptations are reflected in the *arterial oxygen content* (CaO_2 = O_2 content) as follows:

$$CaO_2\left(\text{mL}\cdot\text{dL}^{-1}\right) = 1.34 \times [\text{Hb}]\left(\text{g}\cdot\text{dL}^{-1}\right) \times SaO_2\,(\%) + 0.003 \times paO_2\,(\text{mmHg})$$

(1.34 = O_2-binding capacity of Hb; 0.003 = O_2 solubility in blood)

Regarding cerebral oxygen supply and its high metabolic rate, the central nervous system exhibits significant vulnerability to reduced O_2 delivery, which is well known to manifest in the fact that even a 5-s interruption of blood flow can lead to loss of consciousness. A consistently adequate *cerebral oxygen delivery* (CDO_2) is essential for the optimal activity of all energy-consuming processes.

$$CDO_2\left(\text{mL}\cdot\text{min}^{-1}\right) = \left[\text{CBF}\left(\text{mL}\cdot\text{min}^{-1}\right) \times CaO_2\left(\text{mL}\cdot\text{dL}^{-1}\right)\right]/100$$

(CDO_2 = “cerebral oxygen delivery”; CBF = “cerebral blood flow”)

In summary, cerebral homoeostasis is primarily maintained by an increased cerebral blood flow as a result of cerebral vasodilation, positively supported by acute hyperventilation and the subsequent haematological adaptation. It should be empha-

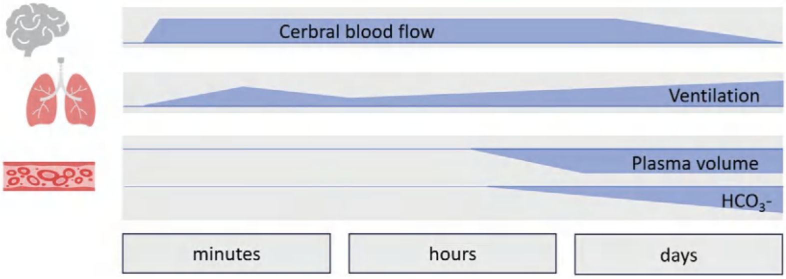


Fig. 4.8 Physiological changes during acclimatisation at high altitude. HCO_3^-—bicarbonate—concentration in blood

sised that these acclimatisation processes also occur at moderate altitude, whereby complete acclimatisation is achieved within a few days (Fig. 4.8).

However, hyperventilation, through the resulting hypocapnia with respiratory alkalosis—which itself induces cerebral vasoconstriction—negatively affects the extent of hypoxic vasodilation.

4.4.2 Change in Acid-Base Balance and Effects on Cerebral Oxygen Supply

Hypoxia is known to stimulate the carotid bodies, leading to hyperventilation and an increase in pH in arterial blood as well as in cerebrospinal fluid. Counter-regulatory mechanisms aiming to normalise pH, such as increased renal HCO_3 excretion, begin within a few hours. Enhanced HCO_3 removal from the cerebrospinal fluid has also been described. While at moderate altitude the increased elimination of HCO_3 is sufficient to normalise pH, this is not possible at high and extreme altitudes, even with maximal HCO_3 excretion: the acid-base balance settles into a so-called partially metabolically compensated respiratory alkalosis.

4.4.3 Cerebral Blood Flow After Acclimatisation

Depending on the absolute altitude, hyperventilation stabilises at a constant level after a certain period. Acclimatised individuals therefore exhibit, at a given altitude, a higher paO_2 and lower $paCO_2$ than non-acclimatised individuals. The time required for ventilatory acclimatisation is approximately 4 days at altitudes around 3000 m, 8 days at 4000 m, and more than 2 weeks at 5000 m. Above 6000 m, between 4 and 6 weeks are required. After successful acclimatisation, the maintenance of PaO_2 is crucial for cerebral O_2 supply. The extent of the increase in cerebral blood flow depends on altitude and results from the interplay between hypoxic cerebral vasodilation and hypocapnic cerebral vasoconstriction. Vasodilation occurs primarily in the large extracranial supplying arteries (internal carotid artery and vertebral artery), large intracranial arteries (middle cerebral artery), and vessels of the pia mater. With prolonged exposure to hypoxia, cerebral blood flow reaches a maximum, decreases after a few days, and stabilises at values between those at sea level and the altitude maximum. The extent to which increased viscosity due to plasma volume reduction and haematological adaptation negatively affects cerebral blood flow remains unclear. Despite a global increase in cerebral blood flow, certain regions are preferentially affected, particularly the posterior circulation, including the brainstem, hypothalamus, thalamus, and cerebellum.

❯ The maintenance of adequate cerebral oxygen supply despite a hypoxic environment requires the balanced interaction of several individual factors, such as hyperventilation, acid-base regulation, and haematological as well as cardiac adaptation. Nevertheless, at extreme altitudes, complete compensation for the reduced O2 partial pressure in ambient air with respect to cerebral oxygen supply is virtually impossible. The extent to which this has negative consequences, especially during prolonged exposure, on structural and functional processes of the central nervous system remains the subject of extensive studies (Zhang and Zhang 2022).

4.5 The Kidney at Altitude

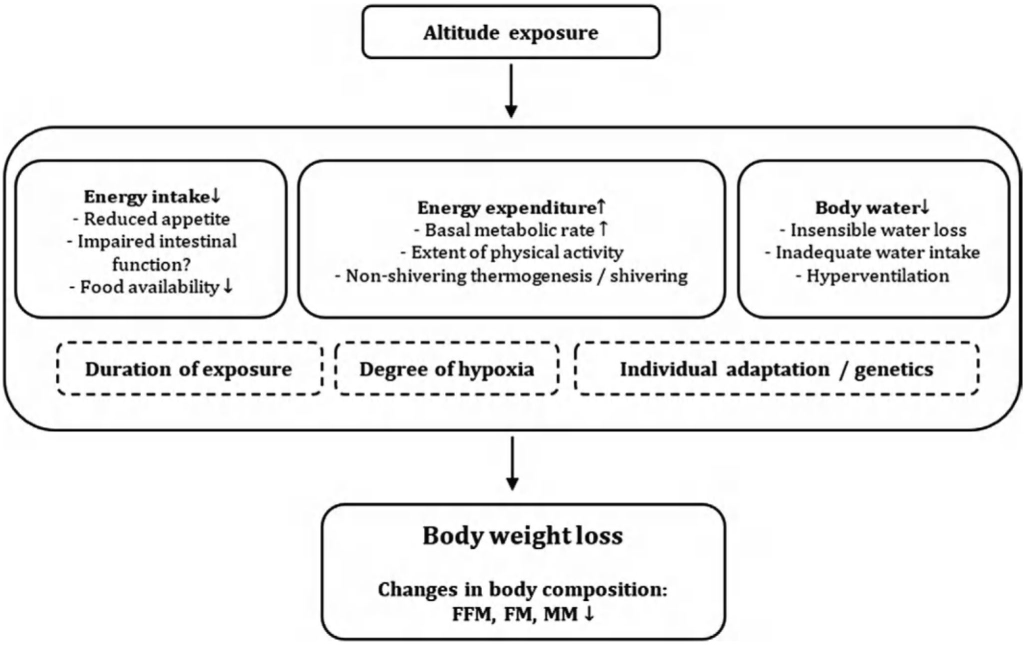
In contrast to other organ systems, in which acute and chronic altitude responses have been studied in detail and acclimatisation pathways are well understood, data regarding the kidney are controversial. As the renal share of cardiac output is 20–25%, resulting in a very high blood flow, the kidney is highly sensitive to hypoxic stimuli. In addition, there are many energy-consuming transport systems that are highly oxygen-sensitive. The renal medulla is particularly affected, as it receives only 10% of total renal blood flow but accounts for 30% of energy-dependent sodium and chloride filtration. Renal O_2 consumption can be divided into approximately 80% for active sodium reabsorption along the nephron and 20% for basal metabolism. Therefore, maintaining renal homoeostasis is of great importance for the overall response of the body to acute and chronic hypoxia (Palubiski et al. 2020; Wang et al. 2022).

The acute hypoxic response of the kidney is influenced by the interaction of various systems, such as ventilatory (hyperventilation with respiratory alkalosis), haematological (increased EPO production), haemodynamic (increased blood pressure and cardiac output, depending on absolute altitude), hormonal adaptations (including renin-angiotensin-aldosterone and ADH), and acid-base regulation (including increased bicarbonate excretion and reduced H^+ elimination to compensate for respiratory alkalosis). At the onset of acclimatisation, a reduction in glomerular filtration rate (GFR) is often observed, accompanied by reduced renal plasma flow. After several days, GFR is assumed to (almost) normalise. Data on sodium excretion and fractional sodium excretion are inconsistent and subject to a dynamic process with multiple influencing factors. In the early phase of altitude exposure, there is an increased loss of salt and water, which, at higher altitudes, leads to enhanced diuresis with reduced antidiuretic hormone and haemoconcentration. Diuresis is only a transient phenomenon during the acclimatisation phase. To avoid excessive plasma volume loss and dehydration, adequate fluid intake during altitude exposure is essential. Endocrinological responses directly affecting renal function include increased sympathetic activity impacting renal blood flow and reduced activity of the renin-angiotensin-aldosterone system.

❯ While in the initial phase of altitude exposure, reduced renal O2 supply is to be expected, various mechanisms lead to normalisation at moderate altitudes. Whether this also occurs at high altitudes has not yet been clearly demonstrated.

4.6 Energy Expenditure and Metabolism at Altitude

A stay at high altitude can affect body composition (e.g. body weight, fat-free mass, and body fat mass) of an individual (Dünnwald et al. 2019; Hamad and Travis 2006). The main factors considered responsible for these changes in body composition essentially include an increase in basal metabolic rate and a negative energy balance (i.e. an imbalance between energy intake and energy expenditure) (Kayser and Verges 2013) (■ Fig. 4.9). The increase in basal metabolic rate is influenced by the degree of hypoxia (Butterfield et al. 1992) and is most pronounced during acute hypoxia (Brooks 2014) and less marked with prolonged exposure (Butterfield et al. 1992; Hannon and Sudman 1973). The initial increase in basal metabolic rate is associated with enhanced sympathetic activity, characterised by elevated catecholamine levels (Mawson et al. 2000). In addition, increased thyroid activity may also play a role, particularly in the longer-term elevation of basal metabolic rate (Luks et al. 2021). Sympathetic activity is attenuated with prolonged exposure at high altitude, resulting in a reduction (compared to acute exposure) in basal metabolic rate. In addition to increased basal metabolic rate, a negative energy balance may also arise from reduced food intake, which may be due either to decreased appetite as a result of changes in appetite-regulating hormones (e.g. ghrelin and leptin) (Gatterer et al. 2023; Westerterp-Plantenga et al. 1999) or, at least at altitudes above 5000 m, partly due to impaired gastrointestinal function (Hamad and Travis 2006). Furthermore, weight loss may be caused by a loss of body water due to inadequate fluid intake and/or insensible fluid loss (water loss via respiration and the body surface) (Gatterer et al.


Altitude exposure
Energy intake↓
- Reduced appetite
- Impaired intestinal function?
- Food availability↓
Energy expenditure↑
- Basal metabolic rate↑
- Extent of physical activity
- Non-shivering thermogenesis / shivering
Body water↓
- Insensible water loss
- Inadequate water intake
- Hyperventilation
Duration of exposure
Degree of hypoxia
Individual adaptation / genetics
Body weight loss
Changes in body composition:
FFM, FM, MM↓

■ **Fig. 4.9** Mechanisms that can modulate body composition at altitude or during a high-altitude expedition. (Modified from Dünnwald et al. 2019)

2013; Kayser 1994). The so-called altitude diuresis may also play a role (Siebenmann et al. 2017b), although more recent data investigating the pure effect of altitude argue against the occurrence of such diuresis (Schlittler et al. 2021). In the first days at altitude, some individuals may also experience fluid retention and thus "overhydration" and weight gain (Gatterer et al. 2013).

It should also be noted that exposure to altitude is often accompanied by exposure to cold. To compensate for heat loss and maintain body temperature in a cold environment, there may be an additional increase in energy expenditure through shivering or non-shivering thermogenesis (Burtscher et al. 2018). In addition, increased energy expenditure due to physical activity (e.g. hiking, mountaineering) can contribute to a negative energy balance (Hamad and Travis 2006; Kayser and Verges 2013; Westerterp et al. 1992). In summary, it can be stated that weight loss at altitude depends on the absolute altitude, duration of stay, individual adaptation to hypoxia, daily fluctuations in body mass, hydration status, and the type of exposure (active or passive stay) (Dünnwald et al. 2019; Kayser 1994).

It should also be emphasised that increased sympathetic activity at altitude is associated not only with an increase in basal metabolic rate but also with enhanced glucose uptake and a shift towards greater carbohydrate oxidation, at least in men (Braun 2008).

Exposure to altitude leads to an increase in basal metabolic rate and may be accompanied by a negative energy balance. These changes may have effects on energy supply (e.g. increased carbohydrate oxidation) and body composition (e.g. weight loss).

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Sleep and Breathing at Altitude

Nikolaus C. Netzer

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"I spent such a terrible night up there that I would not wish it on my worst enemy". This statement was made by the physician Michel Gabriel Paccard after his successful first ascent of Mont Blanc in 1884 (Paccard-Egger 1943). Many mountaineers before and after him have shared this experience of a restless, non-restorative night when camping above 2500 m. As early as 4 years after Paccard's account, in 1888, the Italian scientist Angelo Mosso observed irregular breathing during sleep at high altitude on Monte Rosa and published his findings 10 years later in his seminal textbook *Life of Man in the High Alps* (1898).

5.1 Subjective and Objective Sleep Quality at Altitude

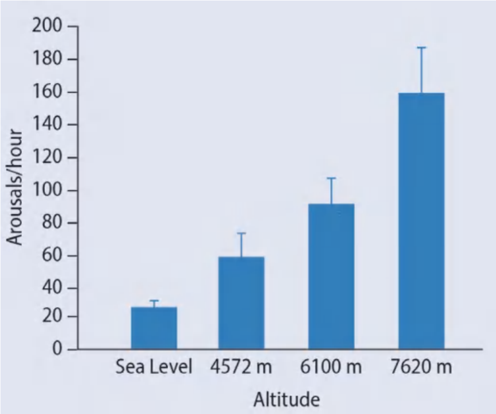
Poor sleep or reduced sleep quality, with increased—at least subjectively perceived—periods of wakefulness and its impact on diminished physical and mental performance during the day, was described by altitude medicine specialists over a century ago. It was also recognised that there is no real acclimatisation effect in this regard and, in contrast to altitude sickness where the symptoms decrease with increasing acclimatisation above a certain altitude or do not persist at the same altitude, sleep quality tends to deteriorate linearly with increasing altitude (Williams 1959).

In the so-called death zone (above 7000 m), sleep is likely to be possible only through total exhaustion; otherwise, the prevailing hypoxia would continuously prevent sleep. This continuous wakefulness may have saved the life of Hermann Buhl, who, according to his own account, after reaching the summit of Nanga Parbat too late during his solo ascent, was forced to spend the night of 3–4 July 1953 standing near the summit (Buhl 2005).

With the electrification of high-altitude shelters and research laboratories, and the development of a universally accepted sleep stage classification by Rechtschaffen and Kales (1968), now replaced by the American Academy of Sleep Medicine (AASM) classification (Berry et al. 2012), it became possible in the 1970s to assess sleep quality and quantity above 4000 m using overnight electroencephalography (EEG), electrooculography (EOG), electromyography (EMG), and electrocardiography (ECG) (Reite et al. 1975).

The objective results of sleep studies conducted in 1975 on six healthy subjects at sea level and at an altitude of 4300 m on Pikes Peak (Colorado, USA) were, at least at that time, consistent with subjective reports:

- A significant reduction in deep sleep stages (delta sleep) at altitude in favour of lighter sleep in stages 1 and 2 and increased wakefulness
- A significant increase in arousals and micro-arousals (brief awakenings lasting seconds, characterised by a shift in EEG activity to the alpha rhythm of 8–12 Hz, increased muscle activity, tachycardia, and elevated respiratory rate, which are not consciously perceived as wakefulness) (■ Fig. 5.1)



■ **Fig. 5.1** Average number of arousals per hour at different altitudes in the Operation Everest II study. (Modified after Anholm et al. 1992, with kind permission of J. D. Anholm, Loma Linda)

- A reduction in “rapid eye movement” (REM) sleep, which is commonly referred to as dream sleep or paradoxical sleep
- Sleep interrupted by multiple periods of wakefulness, i.e. insomnia
- A generally elevated heart rate at night compared to nights at sea level

However, it had already been observed that, in terms of total sleep duration, the subjects achieved an adequate amount of sleep. Thus, sleep was not as poor as mountaineers subjectively described it. Rather, there is a tendency to go to bed earlier and to spend longer overall in bed or in a sleeping bag, and this is perhaps one reason why people are able to cope with the immense physical demands of multi-day high-altitude expeditions.

Ten years later, in the mid-1980s and then in subsequent years, these fundamental changes in sleep at altitudes above 3500 m were largely confirmed in field studies using ambulatory polygraphy and EEGs, or in simulated altitude in a hypobaric chamber up to the sleeping altitude of the South Col of Mount Everest. However, the changes in terms of reduction in delta sleep and REM sleep were not as pronounced as in the 1975 Pikes Peak study (Weil 1985; Anholm et al. 1992; Netzer and Strohl 1999; ▣ Fig. 5.1).

It became apparent that there are individual differences in the extent of sleep disturbance, as is also the case for acute mountain sickness, and that such sleep disturbance is not present in native high-altitude residents such as Sherpas (Wu and Kayser 2006). With a new, validated questionnaire on sleep quality, subjective sleep quality was later found to correlate well with EEG findings. This essentially confirmed the data from the 1970s, 1980s, and 1990s (Jafarian et al. 2008).

More recently, long-term ECG monitoring in Himalayan mountaineers has revealed another pathophysiological change in sleep at high to extreme altitudes that may previously have been underestimated: severe arrhythmias, only partially associated with tachycardia. Palpitations, which are also experienced by mountaineers during the day, can develop at night into rhythm disturbances, which can become brief episodes of ventricular flutter (Woods et al. 2008).

5.2 What Disrupts Sleep at High Altitude?

There are numerous challenges of high-altitude mountaineering which can cause sleep disturbance at high altitude:

- Unfamiliar sleeping environment and, in some cases, uneven, hard, and cold sleeping surfaces
- Coldness and cold, dry air that negatively affect energy balance
- Restrictive clothing and footwear that prevent circulation
- Digestive problems
- Pain from minor injuries such as blisters and abrasions
- Nausea and headache, sometimes associated with altitude sickness, sometimes independent of it
- High nocturnal adrenaline and cortisol levels due to extreme exertion and excitement, which are broken down only slowly and keep the mountaineer awake
- Loud snoring or other noises made by fellow climbers
- Loud wind noise
- Nocturia (increased urination at night) associated with the nocturnal reduction of peripheral altitude oedema (fluid accumulation in the skin and subcutaneous tissue)
- Anxiety

This list could probably be significantly extended by any mountain guide, high-altitude physician, or experienced high-altitude mountaineer; nevertheless, in the end, these are merely “minor issues”. As with the development of specific altitude illnesses, hypoxia is primarily responsible for sleep disturbance at altitude. The altered breathing during sleep caused by oxygen deficiency at high altitude can even be considered the root cause of all the more serious altitude-related illnesses.

> The pattern of sleep at altitude is essentially unchanged compared to that at sea level, but sleep is frequently interrupted by respiratory arousals. REM and deep sleep decrease slightly in favour of light sleep (non-rapid eye movement—NREM—stages 1 and 2).

5.3 Sleep and Breathing in Hypoxia: More Complex Than Previously Thought

During the day, breathing is only partially controlled autonomously by the respiratory centre, and individuals consciously breathe faster or slower to compensate for hypoxia. During sleep, however, the brainstem respiratory centres take over control of breathing automatically. They are guided by signals from chemical sensors (chemoreceptors) that monitor blood gas composition in the carotid artery, which they rely on almost entirely. In particular, the level of CO_2 in the blood is the primary driver. However, and this has scarcely been addressed in the standard literature on high-altitude medicine, every nerve cell in the brain and spinal cord can measure O_2 and, independently of the chemoreceptors in the carotid artery, can influence breathing during sleep via the oxygen content in the central nervous system.

Firstly, however, consider the classical high-altitude physiological model of sleep disturbance caused by hypoxia-induced periodic or paradoxical breathing (Lahiri and Barnard 1983). In this, there is a physiological misregulation between the ventilatory response to oxygen deficiency and the regulation of breathing based on the CO_2 level. Put simply, while breathing rapidly to compensate for the lack of oxygen, too much CO_2 is exhaled, causing the respiratory centre to suppress the breathing reflex, and a pause in breathing occurs. After this pause, rapid breathing resumes to compensate for the now increased oxygen deficit. The cycle then repeats. The technical term for this cycle is a feedback loop. However, the feedback loop depends on the ventilatory drive, which is primarily genetically determined, but is also influenced by age, sex, phase of the menstrual cycle, and other factors. Different individuals respond to the breathing pause, or apnoea, with a stronger or weaker resumption of breathing, and this determines whether an apnoea recurs, and whether hypoxia-induced breathing persists. This individual variability is referred to as "loop gain". For example, loop gain decreases with age. A good overview of these relationships is provided in ◘ Fig. 5.2 and the associated publication by Ainslie et al. (2013). Hypoxia-induced periodic breathing during sleep at altitude (◘ Fig. 5.3) was, as mentioned above, already described by the high-altitude physiologist Angelo Mosso in the nineteenth century (Mosso 1898, ◘ Fig. 5.4; see also the examples from the Everest-II study in ◘ Figs. 5.5 and 5.6).

The apnoeas themselves, along with the associated fluctuations in blood oxygen content, which drops even further during these breathing pauses than it already does at high to extreme altitudes, may be the cause of acute mountain sickness (Burgess et al. 2004), but they are not solely responsible for poor sleep.

It is only the arousals, which occur in association with central apnoeas as part of hypoxia-induced periodic breathing, together with a surge of adrenaline, that are responsible for sleep interruptions causing sleep disturbance. This hypothesis is now widely accepted (Normand et al. 1990; Wickramasinghe and Anholm 1999).

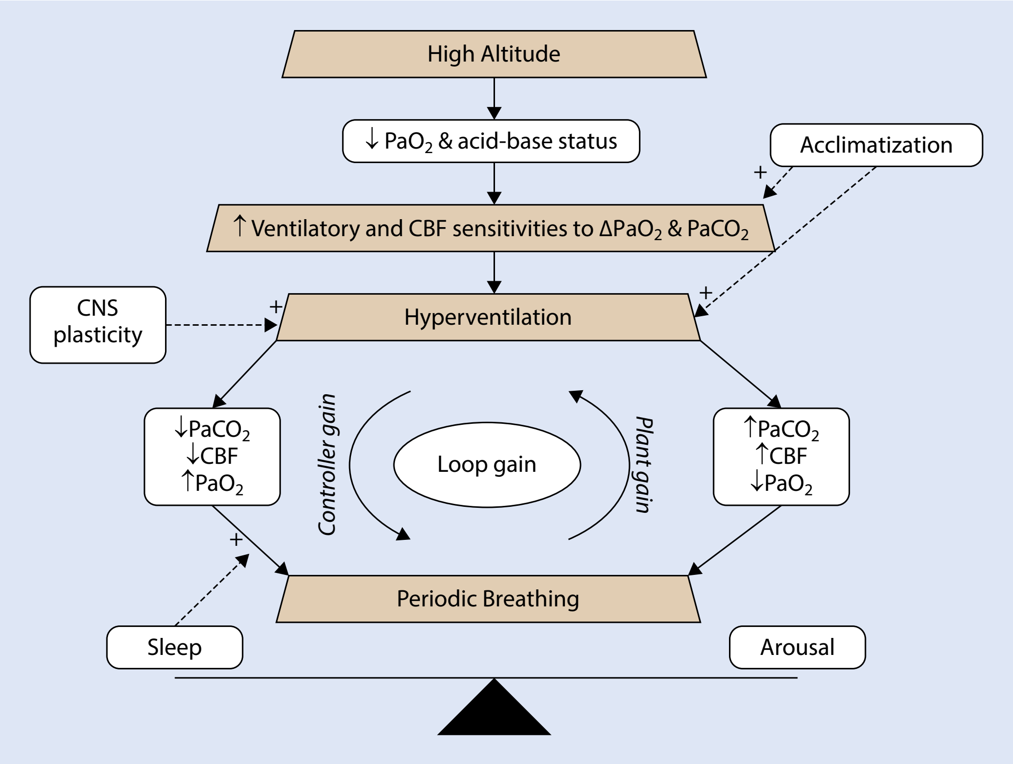

High Altitude
↓ PaO_2 & acid-base status
Acclimatization
+
↑ Ventilatory and CBF sensitivities to ΔPaO_2 & $PaCO_2$
CNS plasticity
+
+
Hyperventilation
↓$PaCO_2$
↓CBF
↑PaO_2
Controller gain
Loop gain
Plant gain
↑$PaCO_2$
↑CBF
↓PaO_2
+
Periodic Breathing
Sleep
Arousal

Fig. 5.2 Diagram illustrating the relationships between factors influencing the "feedback loop" and "loop gain" in periodic breathing. (With kind permission of Peter Ainslie, Vancouver)

Fig. 5.3 The Plaza de Mulas base camp on the normal route of Aconcagua at 4200 m altitude. This is where sleep problems really begin for most mountaineers. (Image credit: N. Netzer)

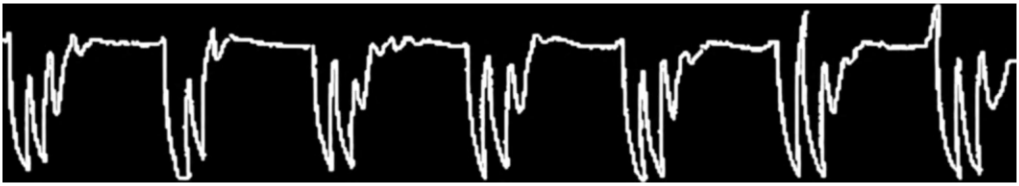


Fig. 5.4 Depiction of hypoxia-induced periodic breathing (downward deflections of respiratory excursions) as measured with a pneumotachograph in 1898. (Modified after Mosso 1898)

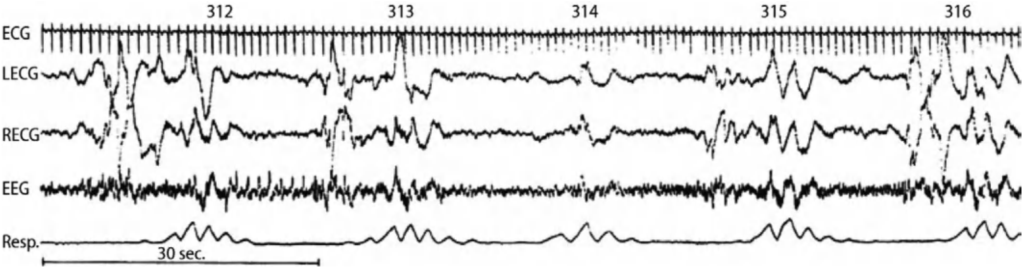


Fig. 5.5 Cheyne-Stokes respiration during REM sleep at an altitude of 6100 m (recording of sleep depth in the bottom line "Resp."). From the Operation Everest II study. (Adapted from Anholm et al. 1992, with kind permission of J. D. Anholm, Loma Linda)

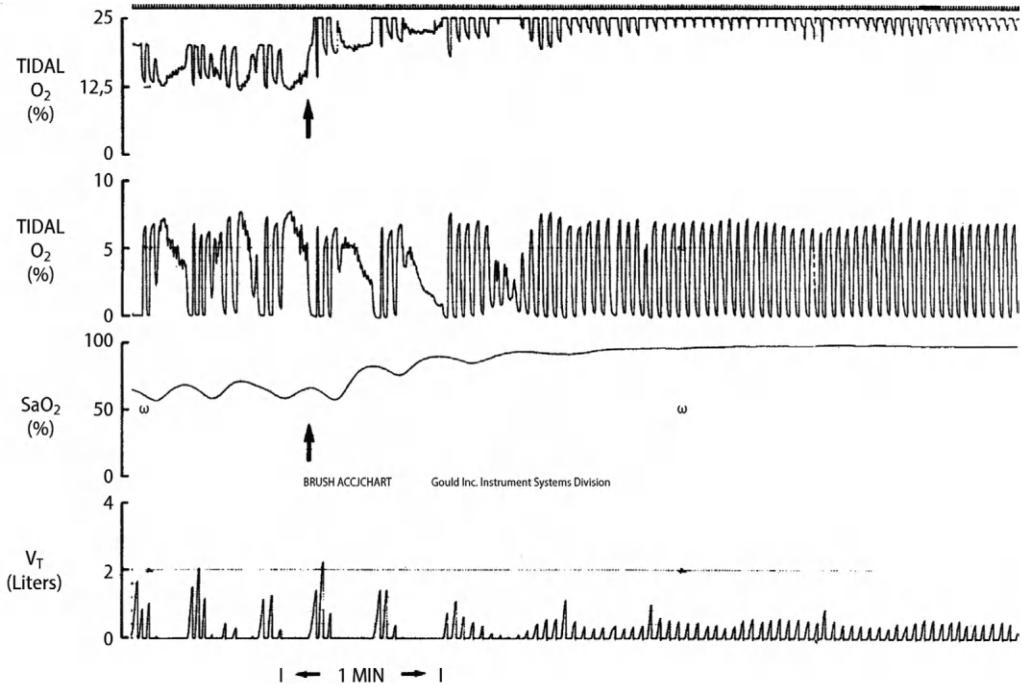


Fig. 5.6 Periodic breathing and declining oxygen saturation (SaO_2) at high altitude. Administration of oxygen (*arrows*) can immediately eliminate Cheyne-Stokes apnoea. From the Operation Everest II study. (Adapted from Anholm et al. 1992, with kind permission of J. D. Anholm, Loma Linda)

Fundamentally, periodic breathing must be regarded as a physiological response of the body to oxygen deficiency, and it remains uncertain to what extent it ensures survival, but at the expense of poor sleep and a possible progression of acute mountain sickness (Milledge 1987; Küpper et al. 2008a, b).

Recent animal studies are attempting to better understand the interaction between central (brain) and peripheral (carotid body) chemoreceptors. It is possible that there are "communication difficulties" between the peripheral sensors and their signal receivers in the brain (Day and Wilson 2009).

It is still not entirely clear why, at extreme altitudes, where CO_2 plays a lesser role in respiratory control and periodic breathing is replaced by a more high-frequency continuous breathing triggered solely by oxygen deficiency and oxygen receptors in the brain, arousals and sleep interruptions still occur. However, there are approaches that may help to unravel these mysteries (◘ Figs. 5.4 and 5.5).

5.4 Hypoxia-Sensitive Cells in the Brain: Their Regulation of Breathing and Influence on Arousals

It is often overlooked in high-altitude medicine and in the training of medical professionals and certified mountain guides that respiratory control via peripheral chemoreceptors, and thus via a rapid drop in carbon dioxide leading to central apnoeas (hypoxia-induced breathing), is only part of the explanation for breathing-related arousals and consequent sleep disruption. There are particularly hypoxia-sensitive cells in the respiratory centre of the brain, specifically in the pre-Bötzinger complex of the respiratory centre (Neubauer and Sunderram 2004).

These cells activate the sympathetic nervous system during hypoxia and directly trigger the release of adrenaline. At correspondingly high adrenaline levels, there is an increased sensitivity to the occurrence of arousals. The "arousal threshold" decreases. Moreover, once the sympathetic nervous system is activated beyond a certain point, neither delta sleep (deep sleep) nor REM sleep (dream sleep) is possible, as the autonomic nervous system must at least be balanced (delta sleep) or the parasympathetic system (cholinergic activity) must predominate over the sympathetic system (adrenergic activity) (REM sleep).

Thus, extreme hypoxia at extreme altitude, with oxygen saturation values consistently well below 80% SaO_2, leads to a persistently high level of adrenaline, which no longer allows normal sleep (see the example in ▶ Sect. 5.1 by Hermann Buhl).

> Cheyne-Stokes respiration predominates during sleep at high altitudes. The extent of Cheyne-Stokes respiration is primarily determined by individual differences in ventilatory drive or "loop gain".

5.5 Snorers and Sleep Apnoea Patients at Altitude

Individuals with sleep apnoea, severe obstructive snoring, and asthma share a common risk in that they are more susceptible at moderate altitudes to a worsening of their symptoms in association with mild hypoxia. This effect is also referred to as the overlap syndrome. Who has not witnessed particularly loud snoring with apnoeic episodes in a mountain hut at around 3000 m in the Alps?

At high and extreme altitudes, however, these symptoms tend to disappear and are replaced by the universally occurring periodic breathing up to 5000 m, or they give way to the high-frequency breathing described in ▶ Sect. 5.4, which is driven by the central neurons in the pre-Bötzinger complex.

The extent to which patients with sleep apnoea or older individuals develop more or less easily hypoxia-induced breathing at moderate to high altitudes due to changes in "loop gain" is not yet sufficiently understood. The use of certain medications may also play a role. For example, high-dose beta-blockers could, by attenuating the normal increase in heart rate and cardiac output during acute hypoxia, trigger an earlier onset of hypoxia-induced periodic breathing at moderate altitudes (Netzer et al. 2020).

> Snoring and sleep apnoea initially increase at moderate to high altitudes. This must be taken into account in individuals with such sleep-related breathing disorders before they embark on a high-altitude expedition.

5.6 Management of Poor Sleep

The management of poor sleep at altitude can be divided into two main groups:

- Non-pharmacological methods (descent, oxygen, positive airway pressure)
- Pharmacological methods (hypnotics, agents that stimulate or regulate respiratory drive)

Other than rapid descent and thus leaving the problem altitude, the administration of oxygen is the most reliable measure at high and extreme altitudes to immediately normalise breathing (◘ Fig. 5.5), eliminate periodic breathing and arousals, and thereby restore normal sleep (Barash et al. 2001) (see also ◘ Fig. 5.6).

While continuous oxygen administration via mask during the day and night is generally impractical and too costly for standard high-altitude expeditions, enriching the ambient air in buildings at high altitude where people live, work, and need to concentrate, such as in the observatories on Mauna Kea, Hawaii (4218 m), or in mines in Bolivia, Chile, and Peru, can play a practical role. Demand systems with oxygen cannulas, which deliver small amounts of oxygen from a portable cylinder via nasal prongs only when frequent Cheyne-Stokes apnoeas occur, are affordable and practical even for standard high-altitude trekking and climbing expeditions.

Methods used to treat obstructive and central sleep apnoea with positive airway pressure at normal altitudes have recently been successfully applied to periodic breathing at altitude and to the treatment of acute mountain sickness. Systems currently in development use masks or helmets with a battery-powered fan. The principle is that the increased inspiratory and end-expiratory pressure raises the partial pressure of oxygen in the air ultimately reaching the lungs via the upper airways (Koch et al. 2008).

Since the early days of high-altitude mountaineering, attempts have been made to improve sleep at altitude using natural remedies (coca, *Ginkgo biloba*, etc.) and later with hypnotics and analgesics. Nowadays, two groups of agents are used either prophylactically or to suppress symptoms that trigger insomnia (Luks 2008). One group is classic centrally acting sedatives, primarily benzodiazepines and benzodiazepine derivatives such as zopiclone. All benzodiazepines also raise the arousal threshold due to their central depressant effect on the respiratory centre (Rühle et al. 2001):

- Flunitrazepam
- Temazepam
- Lorazepam
- Loprazolam
- Zolpidem
- Zaleplon

In addition, preparations that influence respiratory control both centrally and peripherally and reduce periodic breathing are also used:

- Acetazolamide
- Theophylline
- Almitrine

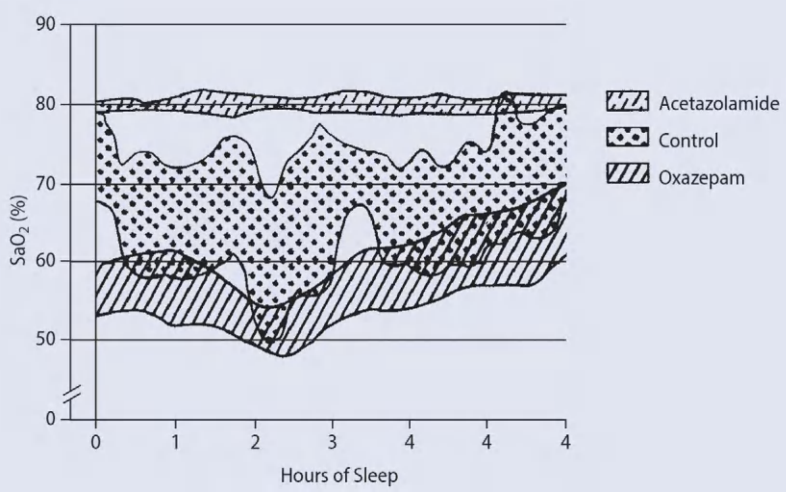
With benzodiazepines, both the central sedative (i.e. sleep-inducing) effect and the mild respiratory depressant effect, which calms breathing, are utilised. A positive effect of benzodiazepines on sleep at high altitude was published in 1979 (Lassere 1979). More recently, there have been well-conducted placebo-controlled studies on temazepam, which was also used early on, and on the zopiclones (Dubowitz 1998; Nickol et al. 2006; Beaumont et al. 2007). All benzodiazepines that were used successfully also had beneficial effects on acute mountain sickness, and in a comparative study, temazepam was superior to acetazolamide in restoring restorative sleep at altitude (Tanner et al. 2013).

Acetazolamide (trade name: Diamox) is the most commonly used agent to improve sleep at altitude by stabilising breathing and for the treatment of acute mountain sickness. It is a carbonic anhydrase inhibitor and maintains blood pH at a lower level by reducing the breakdown of CO_2 and thus acts on the negative feedback loop described above through an indirect effect on the peripheral chemoreceptors. Periodic breathing at moderate to high altitudes occurs rarely or not at all.

As a result, arousals triggered by this mechanism also do not occur; so sleep is less frequently interrupted. It is not known to what extent arousals controlled by the central pre-Bötzinger neurons are also affected. Here, the reduction in pH appears to play a lesser role. The positive effects of acetazolamide on sleep quality at altitude have been published early on and extensively (Sutton et al. 1979) (■ Fig. 5.7). It appears to be superior to all other preparations in suppressing periodic breathing.

Theophylline, which is related to caffeine and theine, is actually a bronchodilator used in chronic bronchitis and pulmonary emphysema. However, it also acts similarly to caffeine, but more strongly. It centrally stimulates the respiratory drive at the level of the central respiratory control neurons in the brain. As it does not act on the peripheral chemoreceptors, it is likely to be inferior to acetazolamide at moderate to high altitudes, but in the low doses in which it is used, it is a very safe and well-established agent (Küpper et al. 2008a, b) (■ Fig. 5.8).

Almitrine is actually an antihypertensive agent that, like theophylline, has a central stimulatory effect on the respiratory centre. Due to the risk of severe allergic reactions



■ **Fig. 5.7** Acetazolamide and the benzodiazepine oxazepam compared in their effects on oxygen saturation during sleep at altitude. (Modified after Anholm et al. 1992, with kind permission of S. R. Sutton, Loma Linda)

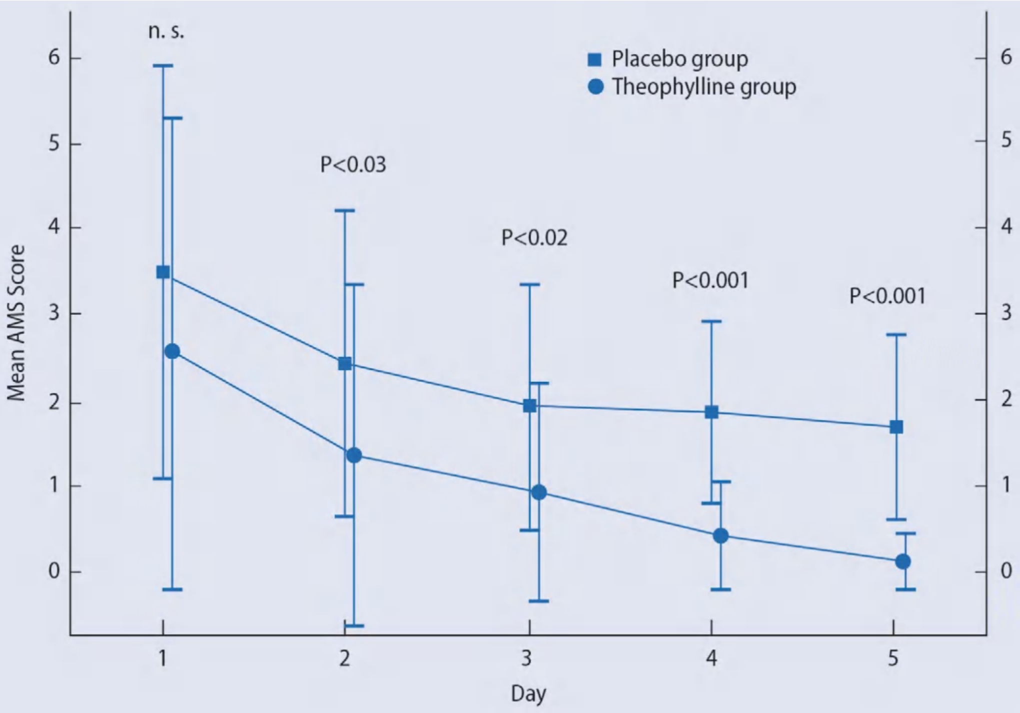


Fig. 5.8 Effects of theophylline administered at bedtime on the development of acute mountain sickness compared to placebo over several days at altitude. The Lake Louise AMS score is significantly lower with theophylline. (Image rights: N. Netzer)

and other side effects, it has virtually disappeared from the market. In a cross-over trial, it was inferior to acetazolamide (Hackett et al. 1987).

That good acclimatisation can prevent altitude sickness is undisputed. However, whether it can also genuinely improve sleep at extreme altitudes remains questionable. As described above, it may be that the body has life-preserving mechanisms that prevent sleep.

Poor sleep at altitude during acute exposure clearly leads to mild cognitive impairment. It does not necessarily result in sightings of a Yeti or other forms of hallucination, but based on a study using the Schuhfried Reaction Test by Pramsohler, cognitive reaction time is already significantly increased after just one night at 3500 m. In contrast, motor reaction time remains unchanged (Pramsohler et al. 2017).

For demanding activities or climbing after overnight stays at higher altitudes, it is therefore advisable either to have several days of acclimatisation beforehand, or at least to be aware of the slowed reaction time and exercise appropriate caution.

> Acetazolamide improves sleep at altitude by indirectly reducing respiratory arousals through the reduction of hypoxia-induced breathing. Certain benzodiazepines, especially temazepam, improve sleep at altitude by general sedation, increasing sleep depth and raising the arousal threshold. Cognitive reaction is already slightly delayed after the first night at moderate altitude.

Conclusion

The pattern of sleep and the percentage distribution of sleep stages are not significantly altered by moderate and high altitudes compared to sleep at sea level. However, sleep is interrupted, mostly by respiratory arousals as a result of central apnoeas in Cheyne-Stokes respiration, which occurs in virtually everyone at altitudes of 3000–6000 m, and is often perceived as unpleasant and non-restorative. At extreme altitudes (6500–8000 m), high-frequency, oxygen-triggered breathing assumes a life-sustaining function, and regular sleep is scarcely possible.

As with acute altitude sickness, acetazolamide is also the best pharmacological treatment for disturbed sleep at altitude, as it reduces respiratory arousals. It is superior to theophylline in this regard. However, whether suppression of Cheyne-Stokes respiration at altitude by medication is advisable remains controversial. The use of more modern benzodiazepines and Z-drugs can also make sleep at altitude more restorative.

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Practice of High-Altitude Tactics: Altitude Acclimatisation

Franz Berghold, Anita Maruna, and Martin Burtscher

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6.1 Altitude Categories

The Earth's atmosphere is primarily characterised by an exponential decrease in air pressure—and thus oxygen pressure—with increasing altitude. Of particular interest is the pressure drop from sea level (760 mmHg, 100%) to the summit of Everest at 8848 m (approximately 250 mmHg, 33.3%).

In simple terms, a high-altitude mountaineering expedition consists of a stepwise progression of subacute, that is, non-sudden, exposure to higher altitudes between sea level and 8848 m. The human body begins to respond to these changes from around a sleeping altitude of 1500 m. The altitude at which one sleeps is especially important for acclimatisation.

The desire to define universally valid altitude categories in terms of human physiological response has not yet been fully realised. In particular, the upper limit of the moderate altitude range remains a matter of debate depending on the perspective. With these caveats, and following the prevailing literature, we distinguish three altitude categories listed in ◘ Table 6.1.

▪▪ Moderate Altitude

Above approximately 1500 m, physical performance begins to decline (in endurance athletes, this may occur even earlier), and minute ventilation increases. Arterial oxygen saturation (SaO_2) changes little, but the arterial partial pressure of oxygen (paO_2) decreases markedly. In the upper range of this category, acute mountain sickness (AMS) is common, particularly as large numbers of tourists (often without adequate acclimatisation) visit this altitude in areas such as the Alps, the world's largest mountainous tourist region.

◘ **Table 6.1** Altitude categories

1500–3000 m	Moderate altitude
3000–5500 m	High altitude
5500–8848 m	Extreme altitude

▪▪ High Altitude

Permanent acclimatisation and thus permanent settlement are possible at these altitudes. Rapid and pronounced hypoxaemia (decrease in SaO_2) during exertion and sleep is characteristic. The most severe forms of altitude illness, high-altitude pulmonary oedema (HAPE), and high-altitude cerebral oedema (HACE) predominantly occur in this altitude range.

▪▪ Extreme Altitude

Hypoxaemia, hypocapnia, and alkalosis predominate at these altitudes. Only short-term stays are possible. The progressive deterioration of physiological processes increasingly overrides acclimatisation.

The transitional zones between these three altitude levels can, understandably, span several hundred metres of elevation as subjective factors (e.g. health status, physical fitness, prior acclimatisation), as well as the terrain, trail conditions, weather, season, latitude, and so on can influence the person's response. Due to differences in prior experience, behaviour, and genetic makeup, individuals do respond very differently to these three altitude ranges.

▪▪ Threshold Altitude

For these reasons, the so-called threshold altitude—a universally valid objective altitude above which acclimatisation is required or altitude illness may occur—is now considered obsolete. Recent observational data (including from genomics research) have made it clear that a threshold altitude is not an objective concept, but rather manifests very differently in each individual. This means that everyone has their own, individual threshold altitude, their own so-called critical altitude. At this point, a comprehensive, complex, and temporally staggered adaptation process (the so-called altitude acclimatisation) begins (Berger and Luks 2023).

One thing is clear: At high and extreme altitudes, humans increasingly enter an environment characterised by a marked decrease in atmospheric pressure and thus in the partial pressure of oxygen, making it an environment to which humans are not indigenous. In other words, humans are not evolutionarily determined for these altitudes. Nevertheless, with adaptation (i.e. acclimatisation), it is possible to survive permanently up to approximately 5500 m, the so-called high altitude and temporarily between 5500–8848 m, the so-called extreme altitude.

However, if individual adaptation to unfamiliar altitudes fails for any reason, altitude illness may develop. This can be fatal in the case of HAPE or HACE. The aim of adaptation strategies is therefore not to accelerate acclimatisation, but to reduce the risk of developing severe altitude illness. Severe forms of acute altitude illness do not occur by chance, but can be largely prevented by appropriate altitude strategies tailored to individual conditions (Berghold and Schaffert 2009).

6.2 High-Altitude Tactics and Adaptation Strategies

Unfortunately, there is a lack of robust evidence on this core topic in altitude medicine, so practical experience remains particularly important. Even the commonly recommended ascent rates (◘ Table 6.2) are actually supported by only limited evidence.

While it seems clear that a slow ascent is generally preventive for AMS, the precise rate at which one should ascend, and *how* slow, remains unclear due to the individual circumstances and accompanying conditions as discussed above. For example, there is not a single controlled study to support the claim that a sleeping altitude difference of 300 m is better, and thus safer in terms of altitude acclimatisation, than one of 500 m (Luks et al. 2019).

◘ **Table 6.2** Selected published guidelines regarding sleeping altitude increments and the use of rest days during ascent to high altitude

Source[a]	**Recommended daily increase in sleeping altitude**	**Use of rest days**
Basnyat and Murchoch (2003)	>3000 m, limit up to 300 m/day	Every 2–3 days or every 1000 m
Hackett and Roach (2001)	>2500 m, limit up to 600 m/day	Every 600–1200 m
MedEx	>3000 m, limit up to 300 m/day	Every 2–3 days
Union Internationale des Associations d'Alpinisme (UIAA)	>2500–3000 m, limit up to 300/500 m depending on terrain	Every third day
Wilderness Medical Society (Luks et al. 2019)	>3000 m, limit up to 500 m/day	Every 3–4 days

[a] Sources: Luks et al. (2019)

6.2.1 On the Evidence for Acclimatisation Strategies

▪ Table 6.2 presents several renowned guidelines with recommendations regarding sleeping altitude increments and rest days. More than four decades ago, Hackett et al. (1976) demonstrated a causal relationship between ascent rate and the incidence of acute mountain sickness (AMS). However, further data addressing the specific question of what "slower is better" actually means are still lacking (Luks 2010).

One of the few robust studies on this core topic in high-altitude mountaineering dates from 1999. The Nepalese researcher, Dr. Basnyat, whilst primarily investigating AMS risk factors, found, among other things, that with each additional night spent over a given altitude range, the risk of AMS decreased by an average of 18.7% (Basnyat et al. 1999).

6.2.2 Central Importance of Molecular Biological Research

Molecular biological research has led to significant advances in the understanding of high-altitude physiology, particularly the discovery of "hypoxia-inducible factors" (HIFs), which play a key role in hypoxia genetics (West et al. 2013). At high altitudes, HIFs influence, among other processes, erythropoiesis, the hypoxic ventilatory response (HVR), and hypoxic pulmonary vasoconstriction (HPV). For their groundbreaking work on the ability of cells to sense and adapt to oxygen availability, Gregg Semenza, Sir Peter Ratcliffe, and William Kaelin were awarded the Nobel Prize in Medicine in 2019. HIFs are also important in the context of AMS and acclimatisation (Mallet et al. 2023). It is currently not possible to predict whether genetic factors will 1 day allow for concrete individual predictions *regarding* susceptibility to AMS, HAPE, and HACE.

As it is well established that, for subacute exposure to hypobaric hypoxia, time is a decisive factor, the rate of altitude exposure is therefore also an important risk factor, even though the exact relationships between ascent rate (i.e. sleeping altitude increment) and the risk of AMS or HAPE/HACE is not yet sufficiently understood. The following questions are of particular interest:

- Do the guidelines apply equally to all individuals?
- Do the recommended sleeping altitude increments refer to the altitude gained each day or to the daily average of the total altitude?
- When should an additional night be spent at the same altitude—before or after a major altitude gain?
- Does pre-acclimatisation enable a faster ascent?

6.2.3 Sleeping Altitude Increment or Ascent Rate?

Which is more important for acclimatisation: the sleeping altitude increment ("rate of ascent") or the daily ascent rate ("speed of ascent")? Much evidence suggests that, during unacclimatised ascents, the vertical altitude difference between the last and the next overnight camp ("sleeping altitude increment") is fundamentally the key factor and appears to be more important for altitude adaptation than the speed of ascent chosen during the day.

Trekking tourists with an average daily sleeping altitude increment of 400 m had a fourfold higher AMS rate than those with 300 vertical metres, and reaching an altitude of 3500 m over 4 days instead of 1 h reduced the risk of AMS by 41% (Bärtsch et al. 2001).

However, individual aerobic capacity plays a significant role in relation to ascent rate. The ascent speed chosen during the day can promote the development of acute mountain sickness if the individual is exercising at or above the anaerobic threshold, whereas this is not the case with moderate exertion (e.g. 50% of maximal oxygen uptake, VO_2max) (Schommer et al. 2012).

With increasing altitude, SaO_2 progressively declines, especially during exertion, as does the already hypoxic induced elevation of pulmonary arterial pressure. This may promote the development of high-altitude pulmonary oedema. The significance of sleeping altitude differences therefore becomes particularly relevant when the rate of ascent during the day reliably remains within the aerobic range (see ► Sect. 6.3.1).

In this context, it must be emphasised that sleeping altitude is of primary importance, rather than the highest altitude reached during the day. Ascending to a high point and then descending as far as possible on the same day appears to be tactically advantageous for acclimatisation.

6.2.4 Individual Altitudes or Average Distance?

Furthermore, the following interesting question arises: Which is more decisive for the prevention of acute mountain sickness—the singular daily sleeping altitude gain or the calculated average ascent distance (total altitude gained divided by the number of ascent days)? In this regard, Meyer (2012) obtained remarkable results on Kilimanjaro: The Machame route, with its abundant individual campsite options, has a better reputation for acclimatisation than the much more frequently used Marangu route, which has fixed lodges with considerable differences in sleeping altitude.

Surprisingly, it was found that both routes had the same incidence of AMS if, as is customary, a rest day (two nights at the same altitude) is taken at Horombo on the Marangu route. Thus, the supposedly more flexible ascent strategy on the Machame route offers no advantage, since the total ascent and the number of days are now the same. In contrast, if the two-night stay at Horombo is omitted, the risk of AMS on this route increases significantly.

It therefore appears that the total altitude gained is the decisive factor, and this is identical for both routes. Evidently, the calculated average sleeping altitude gain over the entire ascent is crucial, rather than any particular single sleeping altitude gain.

6.2.5 Tactical and Therapeutic Rest Day

A tactical rest day (sleeping twice at the same altitude) can be advantageous for clinically healthy individuals in two situations:

- Unfavourable terrain conditions, such as topographically enforced sleeping altitude gains of significantly more than 400 m, can be largely compensated for by rest days. It may be of little importance whether this rest day is taken before or after the large altitude gain (Luks 2010).
- The traditional standard recommendation to take a rest day, i.e. to sleep twice at the same altitude, for every 1000 m of altitude gained, has so far not been confirmed to have an effect on AMS rates (Berghold and Schaffert 2009).

> A therapeutic rest day is the treatment of choice for mild to moderate AMS.

In manifest HAPE, the general recommendation is for rapid passive evacuation to a lower altitude, ideally below 2000 m above sea level. However, in a high-altitude hospital or an outdoor clinic with the possibility of continuous oxygen mask therapy, bed rest may be sufficient as a therapeutic measure instead of evacuation (Luks et al. 2019; Zafren et al. 1996).

6.2.6 How Effective Are Acclimatisation Strategies?

Acknowledging the limited data available only makes empirically based recommendations for effective acclimatisation strategies of greater importance. The following are the current guidelines and recommendations on acclimatisation tactics of the Austrian Society for Alpine and High-Altitude Medicine and the international alpine medicine training courses.

The starting point for any individual consultation should always be the personal history of altitude exposure, if this is available. It must never be forgotten that there are considerable individual differences in the body's response to altitude, as evidenced by the often very different occurrence of AMS symptoms within the same travel group. Nevertheless, high-altitude trekking and mountaineering are possible even for particularly sensitive individuals (with a genetically less favourable disposition), provided that they adhere strictly and uncompromisingly to the fundamental rules of acclimatisation tactics.

The following four key principles form the core of any altitude strategy:

- Do not ascend too quickly!
- Avoid anaerobic exertion!
- Sleep at the lowest altitude possible!
- Never ascend further with symptoms!

The specific implications of this will be discussed below.

6.3 Rate of Ascent

The term "rate of ascent" refers to two aspects: the pace of ascent during the day and the daily sleeping altitude gain. Both are crucial for altitude strategy.

6.3.1 Pace of Ascent ("Speed of Ascent")

The basic principle is: During the acclimatisation phase, exertion should be kept as aerobic as possible. This limits a more pronounced drop in SaO_2, any additional, exertion-induced increase in pulmonary arterial pressure and the associated stress responses that the extra work load induces. Individual regulation of a rational aerobic ascent pace can, for example, be achieved using the one-to-two breathing rhythm: inhale for one step—exhale for two steps—which, of course, depends on individual fitness and may result in very different levels of exertion or ascent pace within a group.

In practice, this breathing rhythm can be maintained on easy terrain with some practice, even with the mouth closed (nasal breathing) and up to an altitude of about 5000 m. This reliably keeps one in the aerobic range. On more difficult or steeper sections, the breathing rhythm is reduced to 1:1 from around 3000 m altitude.

Although most people find the breathing rhythm a very pleasant and easy way to regulate ascent pace, there are always some who have difficulty with conscious rhythmic breathing. As an alternative, the following tried-and-tested method may be used: If you are still able to converse in full sentences with your companions while ascending, you are in the aerobic range.

The exertion during ascent should not exceed 50–60% of VO_2max during the acclimatisation phase, which corresponds to about 60–70% of maximum heart rate (rule of thumb: maximum heart rate = 220—age). Occasional simple checks of heart rate can be performed using a pulse oximetre.

It is also advisable to avoid anaerobic activities after reaching a campsite, such as playing football with the local population (defeat is predictable) or heavy physical work (e.g. shovelling snow, etc.).

The guiding principle is: deliberately slow and economical movements, short daily stages, only light loads, and frequent rests.

> Remember: "Anyone who walks faster than a donkey is a donkey."

6.3.2 Sleeping Altitude Gain ("Rate of Ascent")

The decisive factor for acclimatisation at altitude is probably the sleeping altitude gain. The reduced SaO_2 and the additional increase in pulmonary arterial pressure during sleep due to body position (from upright to horizontal) always represent a critical phase for acclimatisation. This leads to the following tactical rules:

- After reaching your individual "critical altitude", spend several nights at this altitude before ascending further.
- When ascending further: Above this "critical altitude", daily sleeping altitude gains should not exceed 300–400 m. If, due to terrain, a sleeping altitude gain of significantly more than 400 m is unavoidable, two nights should be spent at the previous or next altitude.
- As a general rule, always sleep as low as possible.
- The highest altitude reached during the day can be up to 1000 m above the sleeping altitude.
- Escape routes to lower elevations must always be considered. Special care is required if a camp is located in a depression or behind a pass at a lower level. This means that if there is no direct descent, but you must first ascend several hundred metres before descending into the valley, this must be taken into account.

This sleeping altitude strategy is based on general empirical values, which can vary greatly between individuals and are therefore not equally applicable to all altitude travellers or every high-altitude expedition. Therefore, one should always be guided by the decisive question: How did you feel during the previous night, especially with regard to headache, the key symptom of AMS?

The actual next sleeping altitude should be determined by the answer to this question. In addition, it is advisable to sleep with the upper body elevated as much as possible and to ensure that tents or sleeping quarters are well ventilated. The rules of altitude strategy are particularly important for *those new to high altitude*. However, it is often observed that individuals *with* "altitude experience" means that, depending on their previous experiences, individuals may ascend more quickly or perhaps more slowly than recommended here. Most people instinctively (based on experience) choose the pace that is right for them.

6.4 Additional Tactical Criteria

- Rapid transport from lowland areas to altitudes above 2500–3000 m (e.g. to Leh, Lhasa, Cusco, La Paz, Lukla) by plane, helicopter, cable car, or car always constitutes a particular risk factor and should therefore be avoided whenever possible. If this is unavoidable, it is essential to *spend 2–3 nights* at this sleeping altitude before ascending further.

> No solo trekking! When trekking alone, even on heavily frequented routes, you are always helpless in medical emergencies (especially in cases of HAPE or HACE) and can only rarely expect assistance from others.

- If you feel well at the end of a day's ascent and have time, it is quite beneficial, after a rest at the campsite, to continue ascending slowly and without luggage for about *100–400 m in altitude or more* before returning to the camp. Many high-altitude travellers find this advantageous for their acclimatisation.
- *Conscious hyperventilation:* This allows more oxygen to be extracted from the air. Hyperventilation also lowers the alveolar concentration of carbon dioxide (CO_2), making relatively more oxygen available in the alveoli. However, the quantitative yield decreases as air pressure falls. Ultimately, the marginal benefit of forced hyperventilation is reached when any further oxygen gain is used solely to increase the mechanical work of breathing, as occurs at extreme altitudes.

In contrast to normoxic conditions, consciously forced breathing at altitude does not lead to dizziness or tetany: At an arterial $pO_2 < 45$ mmHg, maximal vasodilation of the cerebral vessels is achieved, and concurrent hypocapnia no longer triggers significant vasoconstriction.

However, hyperventilation cannot improve the oxygen diffusion process itself. The lung is, so to speak, the static, non-trainable, and unchangeable link in the respiratory system. Conversely, any inflammation of the airways impairs both alveolar ventilation and the diffusion process:

- *Increased fluid intake* cannot influence acclimatisation, but it can counteract other relevant risks (thrombosis, thromboembolism, frostbite, etc.). Fatigue, exhaustion, and headaches may also be partly due to fluid loss. Fluid losses (through breathing, sweating, altitude diuresis) should at least be compensated.
- *A carbohydrate-rich diet* (more than 70% of total intake) is not only important for energy supply during high-altitude mountaineering, but also improves the respiratory quotient (lower oxygen consumption compared to fat oxidation). However, whether a carbohydrate-rich diet or carbohydrate supplements alleviate AMS is controversially and has only been accessed in a few studies. The significance of dietary composition for acclimatisation or AMS risk remains disputed.
- *Always watch for early signs of acute mountain sickness!* For example, within a group, it is advisable to monitor each other continuously during ascent. However: air hunger, a feeling of claustrophobia in the tent, facial subcutaneous oedema, sleep disturbances, and nocturnal periodic breathing with typical, brief, repetitive apneas (similar to Cheyne-Stokes respiration) are not signs of AMS, but rather normal altitude-related phenomena.

6.5 Practical Signs of Successful Altitude Acclimatisation

These are the signs of successful altitude acclimatisation:

- Resting heart rate returning to (approximately) personal baseline
- Deeper breathing at rest and during exertion
- Increased urination, especially at night (altitude diuresis)

▪▪ Resting Pulse

An increase in the (morning) resting heart rate by more than 20% above the individual value at low altitude may indicate that the person is currently in the (always critical) acclimatisation phase. If the resting heart rate later returns towards the individual baseline value, this signifies that the acclimatisation process at this altitude has been successfully completed. Respiration: heavy breathing (hyperventilation), especially during exertion, is completely normal even in an acclimatised state. Periodic sleep-related breathing: Sleep interruptions (apneas, hypopneas), accompanied by fitful sleeping, are manifestations of respiratory frequency disturbances, which typically present as repetitive cycles of periodic breathing during sleep at altitude. This altitude-specific phenomenon is, in itself, not a sign of altitude illness and is not considered a trigger for AMS or HAPE. Naturally, it occurs more frequently during the acclimatisation phase, but usually persists even in the acclimatised state during the stay at altitude. Altitude diuresis: The biological purpose of this adaptation to hypoxia is to improve the oxygen content of the blood through haemoconcentration. Increased urine output can therefore be a sign of effective acclimatisation. Urine should be pale and clear, unless discoloured by foodstuffs (e.g. vitamins, electrolyte drinks). Those who do not experience frequent (nocturnal) urination are either dehydrated or poorly acclimatised.

6.6 Pre-acclimatisation

Pre-acclimatisation is a method where the acclimatisation process is initiated before the actual high-altitude activity (trek, expedition) starts. The aim is to reduce the number of acclimatisation days required later or reduce the risk of altitude illness. It becomes attractive when the itinerary is inflexible. For example, when travelling by air to locations above 2500–3000 m or too great sleeping altitude differences occur because of the logistics of the route. By undertaking pre-acclimatisation, time can be saved during the actual ascent, making it possible to reach the desired altitude more quickly (and possibly more safely). This can be achieved, for example, by spending time in mountains near one's place of residence (alpine regions at an altitude of 2000–4000 m; natural altitude) or in simulated altitude (usually normobaric hypoxia; tents or chambers) (Burtscher et al. 2022). Prerequisites for effective pre-acclimatisation are appropriate altitude exposure (altitude and duration of stay) and their temporal proximity to the actual ascent.

6.6.1 Pre-acclimatisation at Natural Altitude

Although this strategy has been known and used for decades, there are only a few studies that have evaluated its effectiveness under controlled conditions. A main effect of such prior altitude exposure is the increase in ventilation at altitude/hypoxia and the associated improvement in the initially low SaO_2. This process of ventilatory acclimatisation reaches a plateau after about 8–10 days at altitude (Sato et al. 1994). In addition to hyperventilation, haemoconcentration (increased diuresis at altitude) also contributes to the elevation of arterial oxygen content ($CaO_2 = Hb \times SaO_2$) and thus to improved oxygen delivery to tissues and submaximal performance. Although 8–10 days (192–240 h) at an altitude of 2000–2500 m is considered optimal for pre-acclimatisation, every single hour spent at this altitude is likely to contribute to acclimatisation (Burtscher et al. 2022). For example, a 6-day stay at 2200 m reduced the incidence of

AMS by half during a subsequent ascent to 4300 m (Beidleman et al. 2009), and after 15 prior 4-h exposures to 4300 m, the development of AMS was completely prevented (Beidleman et al. 2004).

6.6.2 Pre-acclimatisation in Simulated Altitude

Simulated altitude is almost always achieved by applying normobaric hypoxia (mask, tents, chambers). The ambient pressure (air pressure) remains normal, that is unchanged, but the O_2 fraction is reduced below 21%; 16% O_2 corresponds to an altitude of approximately 2100 m and 11% O_2 to an altitude of about 5200 m (when applied at sea level). Since oxygen deficiency (hypoxia) is the main cause of the development of altitude illnesses, pre-acclimatisation under these normobaric hypoxic conditions reduces the risk of altitude sickness to a similar extent as a comparable natural altitude. The advantage of normobaric hypoxia is that it can be deployed at home at any time of day or night for any desired duration of exposure. Acclimatisation effects have been observed after just a few hours of hypoxic exposure (Katayama et al. 2005; Burtscher et al. 2008; Treml et al. 2020). Optimal pre-acclimatisation is likely to be achieved after a total duration of normobaric hypoxic exposure of about 200–300 h; the same time as that for natural altitude. The preferably method would be nights spent in a suitable tent set up at home (Burtscher et al. 2022). The simulated altitude is progressively increased from about 2000 m up to 4000 m, or even higher, depending on individual tolerance and the target altitude. A shorter exposure duration can probably be at least partially compensated by a higher simulated altitude (Fulco et al. 2013). To make optimal use of pre-acclimatisation, it should be continued as close as possible to the time of departure for the planned high-altitude expedition. Although an increasing number of mountaineers are using pre-acclimatisation in normobaric hypoxia, further studies on the optimal individual implementation (as well as on any potential health risks) are urgently needed.

Experience shows: The more often you spend time at alpine altitudes in the months prior to a planned high-altitude expedition outside Europe, the easier the final acclimatisation will be.

6.7 De-acclimatisation

How long does an acclimatised state persist when you return to an altitude below about 1500 m? Once acquired, acclimatisation remains permanent within the relevant altitude range between approximately 2500 and 5500 m, but is lost again within a few days after descending further.

There is little solid data, but only assumptions or empirical values, regarding how long acclimatisation persists at low altitudes. Acclimatisation previously achieved is lost within just a few days after reaching lower elevations. The time until this loss of acclimatisation (the so-called de-acclimatisation) apparently depends on the quality of the prior acclimatisation: Those who were well and thoroughly acclimatised benefit for about 1–2 weeks, while those who were poorly acclimatised retain it for only a few days.

The shorter the stay in the valley between two high-altitude phases, the more likely it is, according to experience, that the renewed ascent to high altitude will be easier. Misapplied, this can lead to neglecting an acclimatisation strategy after an excessively long stay in the valley (at low altitude) during re-ascent, thereby increasing the risk of acute altitude illness.

For both pre-acclimatisation and de-acclimatisation, there are very large individual differences in response. Reliable general rules are therefore not possible in this context either.

> Above one's personal "critical altitude", anyone can develop altitude illness and even die from it, as long as the ascent is sufficiently rapid and high.

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Acute Mountain Sickness

Marc Moritz Berger, Rainald Fischer, and Mahdi Sareban

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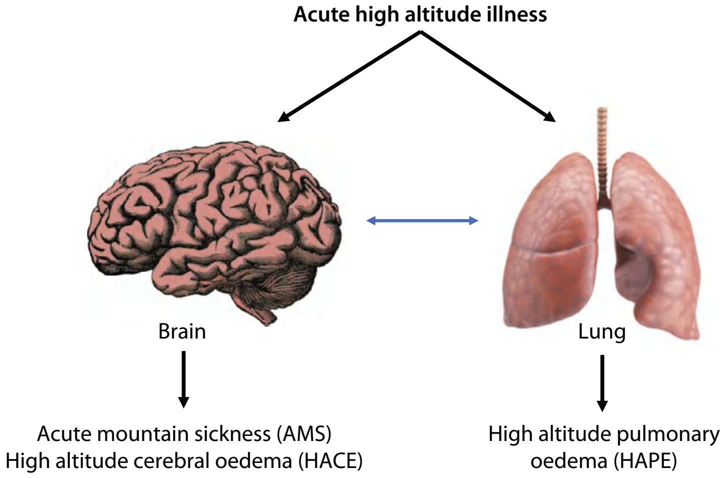
Acute mountain sickness (AMS) is by far the most common form of acute altitude illness. It is unpleasant but not immediately life-threatening. If no further ascent occurs, symptoms usually resolve within 24–48 h. However, if ascent continues despite symptoms, there is a risk at altitudes of approximately 3500–4000 m that severe AMS may progress to high-altitude cerebral oedema.

7.1 Introduction

Ascent to high altitude leads to a decrease in atmospheric pressure and thus a reduction in the inspiratory partial pressure of oxygen. If physiological adaptation is inadequate, the decline in alveolar oxygen uptake results in reduced peripheral oxygen delivery, with the risk of cellular hypoxia and organ dysfunction. This risk is further exacerbated during physical activity due to the additional oxygen demand of skeletal, respiratory, and cardiac muscles (Naeije 2010). If the oxygen deficit is not sufficiently compensated, acute high-altitude illness may develop. Acute high-altitude illness includes AMS, high-altitude pulmonary oedema, and high-altitude cerebral oedema, each of which represents a distinct clinical entity and may be either isolated or occur in combination (◘ Fig. 7.1).

An altitude of 2000–2500 m is considered the lowest threshold for the onset of AMS, whereas the development of high-altitude pulmonary oedema and high-altitude cerebral oedema typically requires elevations above 3500–4000 m. All three forms of acute high-altitude illness may develop in the absence of adequate acclimatisation if ascent is too rapid (Hackett and Roach 2001). This chapter focuses on AMS, while high-altitude pulmonary oedema is discussed in detail in ▶ Chap. 9, and high-altitude cerebral oedema in ▶ Chap. 8.


Acute high altitude illness
Brain
Lung
Acute mountain sickness (AMS)
High altitude cerebral oedema (HACE)
High altitude pulmonary oedema (HAPE)

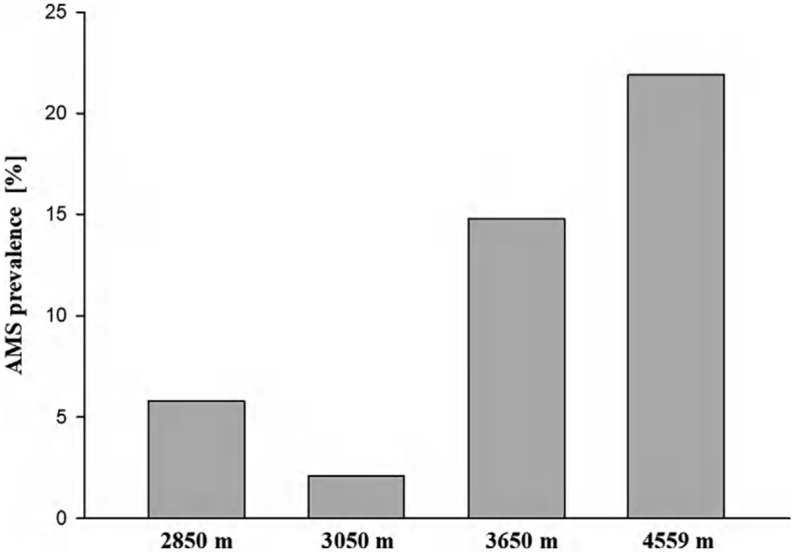
◘ **Fig. 7.1** Acute altitude illness may primarily affect the brain or the lungs. If the brain is affected, AMS or high-altitude cerebral oedema develops. If the lungs are affected, the clinical picture is that of high-altitude pulmonary oedema. Both the brain and lungs may be affected simultaneously, resulting in a mixed clinical presentation

7.2 Epidemiology

Acute mountain sickness (AMS) is by far the most common form of acute high-altitude illness. ◘ Figure 7.2 shows the prevalence of AMS as a function of altitude at four different mountain huts in the Western Alps (Berger et al. 2023). Compared to a study from the 1990s with a similar methodological approach (Maggiorini et al. 1990), the proportion of mountaineers ascending to 4559 m without altitude symptoms has now increased, indicating improved prevention of AMS over the past 30 years.

> ❯ The most important determinants of AMS are the absolute altitude reached, the rate of ascent (in terms of the daily increase in sleeping altitude), the extent of pre-acclimatisation, and the degree of individual susceptibility (Schneider et al. 2002). While the first three factors can generally be controlled, the mechanisms determining the degree of individual susceptibility remain unclear and are presumably genetically determined.

Susceptibility to AMS does not differ between men and women (Berger et al. 2023), whereas children and adolescents are probably less susceptible to AMS than adults (Kriemler et al. 2014). Whether physical exertion exacerbates AMS remains controversial (Roach et al. 2000; Schommer et al. 2012). It is possible that moderate physical activity below the aerobic threshold does not increase the risk of AMS, whereas higher intensities of exertion are likely to increase the risk. Interestingly, well-trained endurance athletes with a high aerobic capacity (66 ± 6 mL/kg/min) have a higher risk of developing AMS on the first day of altitude exposure after rapid, passive ascent to 3450 m than less trained individuals with an average VO_2 max of 45 ± 7 mL/kg/min (Sareban et al. 2019).



◘ **Fig. 7.2** Altitude-dependent prevalence of acute mountain sickness (AMS) in the Western Alps according to the Lake Louise Score (LLS, ◘ Table 7.1). 2850 m = Konkordia Hut, 3050 m = Finsterahorn Hut, 3650 m = Mönchsjoch Hut, 4559 m = Margherita Hut. (Modified from Berger et al. 2023)

7.3 Clinical Presentation of AMS

AMS presents with non-specific symptoms, and to date there is no known biomarker or parameter that reliably indicates the presence of AMS. Symptoms typically occur within the first 3–72 h after ascent to altitudes above 2000–2500 m.

> The main symptom of AMS is headache, which is accompanied by non-specific symptoms such as loss of appetite or nausea, vomiting, fatigue or weakness, and dizziness. In general, AMS is diagnosed when, in the presence of headache, the severity of symptoms is described as at least moderate (Roach et al. 2018). However, in some individuals (probably about 5%), AMS is not diagnosed when it should have been if headache is considered a mandatory symptom (Sampson et al. 1983; West 2011).

In scientific studies, AMS is most commonly diagnosed using the so-called Lake Louise Score (LLS) (Roach et al. 2018) or the AMS-C Score (Sampson et al. 1983; Beidleman et al. 2007). These are questionnaires that record the symptoms associated with acute altitude exposure and quantify their severity. The LLS diagnoses AMS when the score is at least 3 (◘ Table 7.1), with symptoms required to be related to a recent gain in altitude and at least one point is assigned for headache. For the AMS-C Score, respondents indicate how they feel on a scale from 0 (no symptoms) to 5 (most severe symptoms). These scores are multiplied by a symptom-specific weighting factor, and then the sum of the scores is calculated and multiplied by 0.193. A diagnosis of AMS is made if the total score is ≥0.7. Here too, symptoms must be related to a recent altitude gain, but headache is not mandatory for diagnosis.

◘ **Table 7.1** Symptoms and scoring for calculation of the Lake Louise Score

Symptoms	**Points**
Headache	
Not at all	0
Mild headache	1
Moderate headache	2
Severe incapacitating headache	3
Gastrointestinal symptoms	
None, good appetite	0
Poor appetite or nausea	1
Moderate nausea or vomiting	2
Severe incapacitating nausea and vomiting	3
Fatigue/weakness	
Not at all	0
Mild fatigue/weakness	1
Moderate fatigue/weakness	2
Severe incapacitating fatigue/weakness	3
Dizziness/light headedness	
Not at all	0
Mild dizziness/light headedness	1
Moderate dizziness/light headedness	2
Severe incapacitating vertigo/dizziness	3

Roach et al. (2018)
[a]For details, see text

For everyday use in the mountains and for non-medical professionals, these questionnaires are of limited or no practical use. An alternative is the clinical functional score, which assesses and rates the degree of subjective impairment in the presence of symptoms associated with a recent altitude gain (◘ Table 7.2).

Table 7.2 Clinical functional score for the assessment of acute mountain sickness

Symptoms	Points
No limitation of activity	0
Mild limitation of activity	1
Moderate limitation of activity	2
Severe limitation of activity	3

If clinical symptoms are present and the clinical functional score is ≥2 points, in the context of an acute gain in altitude, AMS should be assumed and managed accordingly (Meier et al. 2017).

AMS itself is unpleasant but not immediately life-threatening. In most cases, symptoms resolve spontaneously within 24–48 h if no further ascent occurs. However, if symptoms of severe AMS progress (including nausea and headache unresponsive to antiemetics and analgesics), a life-threatening high-altitude cerebral oedema may develop (Wilson et al. 2009). This leads to impaired consciousness, ataxia, and ultimately death if not treated appropriately (Bartsch and Swenson 2013).

7.4 Pathophysiology of AMS

The pathophysiology of AMS remains incompletely understood. Numerous studies over the past 50 years have failed to identify consistent or relevant correlations between the occurrence of AMS and individual pathophysiological factors (Berger et al. 2020a, b). Despite the prolonged search for a test that reliably predicts susceptibility to AMS, the best predictor of altitude tolerance currently remains the medical history regarding previous altitude exposures with similar pre-acclimatisation (Bartsch 2014). If AMS symptoms have occurred in the past, the likelihood of developing AMS again under similar conditions is high.

In general, it is assumed that AMS symptoms reach their maximum after the first night at a new, higher altitude.

However, a pooled analysis of data from four different studies conducted at altitudes between 3450 and 4559 m suggests that there may be three distinct groups susceptible to the development of AMS (Berger et al. 2020a). While at a given altitude, approximately 40% of AMS-positive mountaineers reach the maximum severity of symptoms on the first day of altitude exposure, a further 40% reach their maximum on the second day. Finally, in about 20% of mountaineers with AMS, symptom severity increases over time, peaking on the third day of altitude exposure (Berger et al. 2020a). It is conceivable that these three distinct groups occur because of distinct pathophysiological signalling cascades, which may also explain the lack of association between individual pathophysiological factors and the occurrence of AMS described above. However, confirmation of these data by further analyses is pending.

The prevailing view is that high-altitude cerebral oedema (see ► Chap. 8) represents the pathophysiological end stage of AMS (Wilson et al. 2009). However, this view is subject to ongoing debate (Turner et al. 2021).

Hypoxia is the central element in the pathophysiology of AMS. Typically, arterial oxygen saturation (SaO_2) and arterial oxygen partial pressure (PaO_2) are on average slightly lower in individuals with AMS compared to healthy controls at a given altitude. However, these values show such high interindividual variability that drawing conclusions about the risk or presence of AMS based on SaO_2 or PaO_2 is unreliable. While at an altitude of 4559 m some mountaineers with a SaO_2 of 80–85% meet the criteria for AMS, others with a SaO_2 of 75% do not. Factors that may contribute to more pronounced hypoxaemia in AMS-positive individuals include a lower hypoxic ventilatory response (HVR) (Richalet et al. 2012), a higher basal metabolic rate (metabolism) (Sareban et al. 2019) as well as reduced oxygen diffusion due to an (subclinical) interstitial pulmonary oedema induced by high-altitude exposure (Cremona et al. 2002).

Subsequently, hypoxaemia leads to the activation of various processes. Cerebral blood flow increases to maintain oxygen supply to the brain (Wilson et al. 2011). As a result, blood pressure in the cerebral vessels rises, particularly if venous outflow is also restricted, as may occur in the supine position or when the head is turned to the side (Wilson et al. 2009). The increase in cerebral blood flow and blood pressure in the cerebral vessels promotes cerebral oedema with a rise in intracranial pressure, which could explain the typical symptoms of AMS such as headache, as well as associated nausea and vomiting (Sanchez del Rio and Moskowitz 1999; Bailey et al. 2009). However, current data do not show a clear association between the mild increase in brain volume observed in hypoxia (Kallenberg et al. 2007) and the occurrence or severity of AMS. Furthermore, individuals with AMS do not show elevated serum concentrations of neurofilament proteins, which would indicate neuro-axonal injury, compared to healthy controls (Sareban et al. 2021).

Another consequence of hypoxaemia may be an imbalance of the autonomic nervous system, with a relative predominance of parasympathetic over sympathetic activity, which can lead to typical AMS symptoms such as headache, nausea, and dizziness (Holmqvist et al. 1986; Straube et al. 2007). This could explain why endurance-trained athletes, who have higher parasympathetic activity due to their training, showed a higher incidence and severity of AMS on the first day of altitude exposure at 3450 m compared to less well-trained controls (Sareban et al. 2019).

For a more detailed discussion of the pathophysiology of AMS, reference is made to comprehensive review articles on this topic (e.g. Berger et al. 2020b; Turner et al. 2021; Frank et al. 2022).

7.5 Prevention of AMS

There are a variety of non-pharmacological and pharmacological options for the prevention of AMS, which are largely based on the physiological and pathophysiological considerations described above. Since high-altitude cerebral oedema is considered the end stage of very severe AMS, the preventive measures described here for AMS also apply to high-altitude cerebral oedema.

> The primary focus in the prevention of AMS is on non-pharmacological measures, which take into account the intended altitude exposure, individual altitude history (i.e. individual susceptibility), planned ascent rate, and the extent of pre-acclimatisation.

7.5.1 Non-pharmacological Measures

Current guidelines for ascents to altitudes above 3000 m recommend that the sleeping altitude should not be increased by more than 500 m per day, and that there should be a rest day every 3–4 days (Luks et al. 2024). This is considered one of the most important preventive measures. If adherence to this conservative ascent profile is not possible, for example for logistical reasons (terrain, environmental factors), additional acclimatisation days should be scheduled either before or immediately after stages with greater altitude gains. However, it should be noted that altitude tolerance varies greatly between individuals, so that some people can tolerate much faster ascent profiles without developing AMS.

In addition to a moderate ascent rate, pre-acclimatisation at lower altitudes is considered another important preventive measure. However, the optimal individual approach for adequate pre-acclimatisation is difficult to predict. In principle, pre-acclimatisation should be carried out at a high enough altitude to trigger adaptation processes, but low enough not to cause AMS or discomfort. For example, a 1-week stay at 2200–3000 m led to a significantly reduced risk of AMS during a subsequent stay at 4300 m (Beidleman et al. 2009). Similarly, spending at least 5 days at altitudes above 3000 m in the 2 months prior to an ascent to 4500 m was associated with a reduced risk of AMS (Schneider et al. 2002).

The evidence regarding the effectiveness of artificial hypoxia, such as that produced by commercially available altitude tents, shows conflicting results for the prevention of AMS. Current guidelines indicate that altitude tents may be considered a preventive measure, provided that sufficiently long and regular exposure over several weeks is possible without impairing sleep quality (Luks et al. 2024).

> If a slow ascent or a pre-acclimatisation period is not possible in individuals known to be susceptible to AMS, pharmacological prophylaxis should be considered.

7.5.2 Pharmacological Measures

Pharmacological prevention of AMS should be based on an individual risk assessment and take into account other factors such as personal altitude history or susceptibility, ascent profile, and the absolute altitude reached (for risk stratification, see also ► Chap. 8 on high-altitude cerebral oedema). In situations with low AMS risk, pharmacological prophylaxis should not be used, as this would otherwise limit the options for pharmacological treatment of AMS.

> The gold standard for pharmacological prevention of AMS is the carbonic anhydrase inhibitor acetazolamide.

The optimal dose of acetazolamide for AMS prevention remains uncertain. In most cases, 125 mg twice daily should be sufficient (Low et al. 2012). An increase to 250 mg twice daily can be used without difficulty in situations with high AMS risk (◘ Table 7.3). Doses of 250 mg three times daily are also an option, although they are associated with more side effects and are therefore not recommended as the standard dose for AMS prevention. Typical side effects include paraesthesia in the fingers, increased diuresis, and taste disturbances. For children, the recommended acetazolamide dose is 2.5 mg/kg (up to a maximum of 125 mg) every 12 h (Luks et al. 2024). Acetazolamide is usually started on the evening before ascent and should be continued until descent or for 2–3 days at the final altitude.

In cases of intolerance or contraindications to acetazolamide, dexamethasone can be taken at a dose of 4 mg twice daily (alternatively, 2 mg four times daily) (Luks et al. 2024; Luks and Hackett 2022). In situations with a high risk of AMS, the dose can be increased to 4 mg every 6–8 h (◘ Table 7.3). However, dexamethasone is not the first-line drug for the prevention of AMS due to its side effect profile and should only be used where acclimatisation is not possible, for example, in rescue operations. Because of the risk of adrenal suppression, dexamethasone should be tapered over a week and not

Table 7.3 Recommended pharmacological prophylaxis and treatment [a] of acute mountain sickness (AMS) in adults

Indication	Medication	Administration	Dose
Prophylaxis	Acetazolamide	Oral	Moderate risk: 125 mg every 12 h
			High risk: 250 mg every 12 h
	Dexamethasone	Oral	Moderate risk: 4 mg every 12 h
			High risk: 4 mg every 6–8 h
Treatment	Ibuprofen	Oral	600 mg every 8 h (for headache)
	Metoclopramide	Oral	10 mg every 8 h (for nausea)
	Acetazolamide	Oral	250 mg every 12 h
	Dexamethasone	Oral, i.v.	4 mg every 6 h (in severe AMS)

[a] As AMS is caused by hypoxia, like all forms of acute high-altitude illness, descent to lower altitude is the primary treatment as it addresses the cause. If descent is not possible, the administration of oxygen represents a suitable alternative treatment (for details see text)

stopped abruptly if it has been taken for more than 5–7 days. Dexamethasone is not recommended for the prevention of AMS in children due to a lack of data.

7.6 Treatment of AMS

As all forms of acute high-altitude illness are caused by hypoxia, descent to lower altitudes is the primary treatment for all forms of acute high-altitude illness, including AMS. If descent is not possible, for example due to the terrain or because the patient is too ill, administration of oxygen is an appropriate alternative to descent. The flow rate should be adjusted to relieve symptoms. Typically, a peripheral SpO_2 of around 90% is sufficient. If neither descent nor oxygen administration is possible, the use of a portable hyperbaric chamber is another therapeutic option (Bartsch et al. 1993).

The measures described above also apply to the treatment of severe forms of AMS. However, AMS is usually mild to moderate and can be managed by a rest day at the same altitude. For headache, simple analgesics such as paracetamol or ibuprofen are usually effective. For nausea, antiemetics such as metoclopramide can be taken (Bartsch and Swenson 2013).

In individuals with more severe AMS or in cases where conservative measures are ineffective, dexamethasone can be administered at a dose of 4 mg every 6 h (Luks et al. 2017). Dexamethasone is highly effective in the treatment of AMS.

In principle, dexamethasone for the treatment of AMS can also be combined with acetazolamide (250 mg twice daily). However, the therapeutic effect of acetazolamide for AMS is not well established (Grissom et al. 1992; Luks et al. 2017) and has been examined by only one study. If these measures do not achieve a sufficient therapeutic effect, descent in altitude of at least 500–1000 m should be undertaken, or descent should continue until symptoms resolve (Luks et al. 2024). Descent, especially in cases of severe AMS, should never be attempted alone but always with a companion.

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High-Altitude Cerebral Oedema

Marc Moritz Berger and Franz Berghold

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8.1 Introduction

High-altitude cerebral oedema (HACE), along with acute mountain sickness (AMS; ► Chap. 7) and high-altitude pulmonary oedema (HAPE; ► Chap. 9), represents one of the three classical forms of acute high-altitude illness. All three forms of acute high-altitude illness may develop in the setting of insufficient acclimatisation when ascent is too fast (Hackett and Roach 2001). AMS, HACE, and HAPE can occur either in combination or independently (see also ► Chap. 7). While the lower threshold for the onset of AMS is generally considered to be 2000–2500 m, the development of HACE typically requires altitudes above 3500–4000 m (Bartsch and Swenson 2013). However, the lowest altitude at which HACE has been reported is 2100 m (Dickinson 1979). Cases of HACE have also been documented at altitudes above 7000 m (Clarke 1988).

> It is generally assumed that HACE represents the end stage of severe AMS (Luks et al. 2024). However, there are also cases in which HACE has been diagnosed without preceding AMS (Hackett and Roach 2004).

HACE was first described in 1913 by Ravenhill, a physician working in the Collahuashi mines of northern Chile, as "Puna of the nervous type". The condition subsequently faded from attention until, about 50 years later, numerous cases of HACE were documented among Indian troops during military conflict with China (West 2014).

8.2 Epidemiology

HACE is the rarest form of acute high-altitude illness but is associated with the highest mortality rate. Without appropriate treatment, HACE is almost always fatal (Bartsch and Swenson 2013). At altitudes between 4000 and 5000 m, the estimated prevalence of HACE is 0.5–1% (Bartsch and Swenson 2013). The presence of HAPE significantly increases the risk of developing HACE, probably due to the more pronounced hypoxaemia caused by pulmonary oedema. For example, in the French Alps, 13% of 52 patients with HAPE were found to have concomitant somnolence or coma (Gabry et al. 2003). Similarly, in the Colorado Rockies, 14% of 150 patients with HAPE also had HACE (Hultgren et al. 1996). In the Swiss Alps, HACE was detected in 20% of patients who were evacuated by helicopter due to HAPE (Hochstrasser et al. 1986). Reports of HACE in children are rare, which may also be because, fortunately, the population of children who ascend rapidly to high altitudes is small.

> Due to the rarity of this condition, there is no systematic analysis of risk factors for the development of HACE. As HACE generally arises from a severe case of AMS, it is likely that both conditions share the same risk factors. These include, in particular, the absolute altitude reached, the rate of ascent (in terms of the daily difference in sleeping altitude), the degree of prior acclimatisation, and individual susceptibility (see also ► Chap. 7 on AMS).

8.3 Clinical Presentation of HACE

The cardinal symptom of HACE is encephalopathy, which manifests as ataxia and/or impaired consciousness. Typically, symptoms of severe AMS have been present in the preceding 24–48 h. Severe headache is usually, but not always, present. This is followed by drowsiness and subtle psychological changes. The patient often appears withdrawn and apathetic. Fatigue progresses to the point where the patient is no longer able to adequately care for themselves. The affected individual dresses inappropriately for the altitude and ambient temperature and neglects food and fluid intake. Anorexia is almost always present, whereas nausea and vomiting are less common. A characteristic feature is an elevated body temperature of around 38 °C. Increasing confusion, possibly with hallucinations, and ataxia subsequently develop. If gait instability is suspected, this can be objectively assessed using a simple heel-to-toe test. For this, the patient is asked, without shoes or rucksack, to walk along a straight line drawn on level ground, placing 1 ft directly in front of the other. If the patient repeatedly steps off the line, requires support, or even falls, the presence of ataxia and gait instability is confirmed.

> Without treatment, symptoms can progress to coma within a few hours. If left untreated, the condition is fatal.

In principle, the presence of HACE can be demonstrated by MRI as a visually detectable cerebral oedema, particularly in the splenium of the corpus callosum (Hackett et al. 1998). However, this diagnostic approach is, of course, not available in remote environments. In patients who have survived HACE, T2*-weighted MRI scans of the brain reveal microhaemorrhages in the region of the corpus callosum, which can be detected as haemosiderin deposits for years afterwards (Schommer et al. 2013). This is particularly important for the retrospective diagnosis of previous HACE.

Differential diagnoses to be considered in HACE are listed in ◘ Table 8.1.

Due to the limited diagnostic options in the field, clinical assessment should be as precise as possible, following the principle that any suspicious symptomatology should be considered HACE until proven otherwise.

◘ **Table 8.1** Possible differential diagnoses of high-altitude cerebral oedema

Acute psychosis	**CO poisoning**
Migraine	Exhaustion
Brain tumours	Dehydration
Stroke	Diabetic ketoacidosis
Transient ischaemic attacks (TIA)	Hypoglycaemia
Transient global amnesia (TGA)	Hyponatraemia
CNS infection	Hypothermia
Retinal vein thrombosis	Viral/bacterial infection
Poisoning (toxins, drugs, alcohol)	Seizure

8.4 Pathophysiology of HACE

As already mentioned in ► Sect. 8.1, it is generally assumed that HACE represents the pathophysiological and clinical end stage of severe AMS. Accordingly, reference is made here to the detailed description of the pathophysiology of AMS in ► Chap. 7.

In addition to the processes occurring in AMS, the pathophysiology of HACE is likely to involve increased vascular permeability due to elevated oxidative stress, inflammation, or upregulation of vascular endothelial growth factor (VEGF) (Tissot van Patot et al. 2005; Bailey et al. 2009). Furthermore, hypoxia-induced inhibition of energy-dependent, transcellular ion transport may lead to cytotoxic (intracellular) oedema (Kallenberg et al. 2007), which in turn, through an increase in brain volume, results in raised intracranial pressure.

A schematic overview of the pathophysiological processes that may lead from

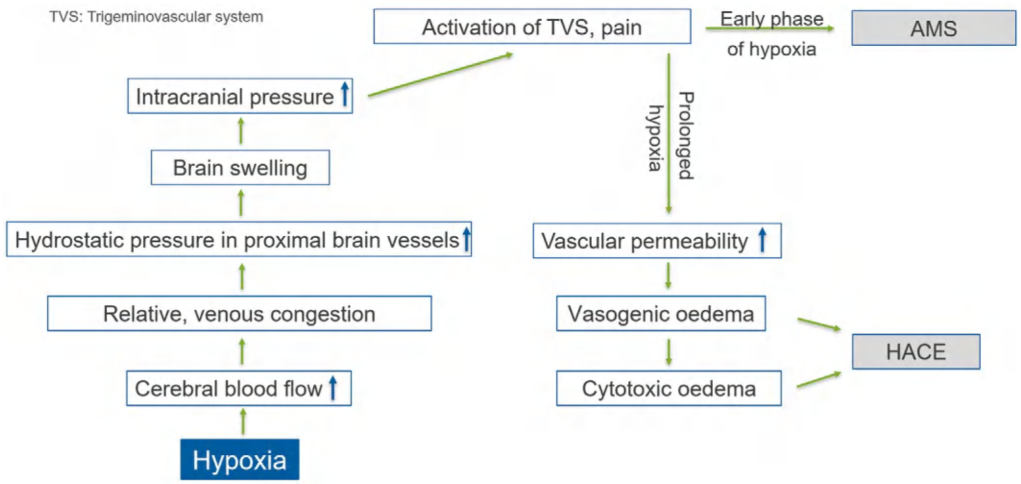
TVS: Trigeminovascular system
Activation of TVS, pain
Early phase of hypoxia
AMS
Intracranial pressure ↑
Brain swelling
Hydrostatic pressure in proximal brain vessels ↑
Relative, venous congestion
Cerebral blood flow ↑
Hypoxia
Prolonged hypoxia
Vascular permeability ↑
Vasogenic oedema
Cytotoxic oedema
HACE

Fig. 8.1 Schematic representation of possible mechanisms that may be relevant in the pathophysiology of AMS and HACE. (Modified from Berger et al. 2020a.) For details, see text and ► Chap. 7. *TVS* trigeminovascular system

hypoxia to AMS and subsequently to HACE is shown in Fig. 8.1 and can also be found in Berger et al. (2020a).

8.5 Prevention of HACE

For the prevention of HACE, the same measures apply as for the prevention of AMS. Reference is therefore also made here to the detailed description of preventive measures in ► Chap. 7.

> The focus of prevention is on non-pharmacological measures, considering the intended maximum altitude, individual altitude history (i.e. individual susceptibility), planned rate of ascent, and the extent of pre-acclimatisation.

8.5.1 Non-pharmacological Measures

According to current guidelines for ascents to altitudes >3000 m, the sleeping altitude should not be increased by more than 500 m per day, and a rest day should be taken every 3–4 days (Luks et al. 2024). In addition to a moderate rate of ascent, pre-acclimatisation at lower altitudes is considered another important preventive measure. However, the optimal individual approach for adequate pre-acclimatisation is difficult to predict. In principle, pre-acclimatisation should be carried out at an altitude high enough to trigger adaptation processes, but low enough to avoid AMS and discomfort. When aiming for altitudes >4000 m, the ascent should be made in several daily stages. Alternatively, and ideally in addition, acclimatisation tours at intermediate altitudes should be undertaken as preparation. For example, in preparation for trekking or mountaineering with rapid ascent to >4000 m, acclimatisation tours in the European Alps with overnight stays at the highest possible elevations are recommended (Schommer and Bartsch 2011).

8.5.2 Pharmacological Measures

In principle, pharmacological prophylaxis for AMS is necessary for only a minority of

Table 8.2 Risk stratification for the development of AMS or HACE[a]

Low risk	Individuals with no history of AMS/HACE and a planned target altitude <2800 m Ascent to 2500–3000 m over ≥2 days, with subsequent increases in sleeping altitude of <500 m/day and 1 additional acclimatisation day for every 1000 m of altitude gained
Moderate risk	Individuals with a positive history of AMS ascending to 2500–2800 m within 1 day Individuals with no history of AMS ascending to >2800 m in 1 day All individuals ascending at a rate of >500 m/day (increase in sleeping altitude) at altitudes >3000 m, but who include an acclimatisation day for every 1000 m of altitude gained
High risk	Individuals with a positive history of AMS ascending to >2800 m in 1 day Individuals with a history of HACE or HAPE Individuals ascending to >3500 m in 1 day Individuals ascending at a rate of >500 m/day (increase in sleeping altitude) at altitudes >3000 m, without additional acclimatisation days

Modified from Luks et al. (2024)

[a] The altitude values refer to sleeping altitude. The recommendations apply to individuals who are not pre-acclimatised and who are ascending from the valley (<1200 m)

AMS acute mountain sickness; *HACE* high-altitude cerebral oedema; *HAPE* high-altitude pulmonary oedema; *m* metres of altitude

high-altitude travellers and should be reserved for those with a history of AMS or HACE (particularly if these occur regularly during comparable altitude exposures). Pharmacological prophylaxis may also be considered for those planning an ascent with a high risk of AMS.

Risk stratification for the development of AMS or HACE can be performed as follows (Table 8.2):

The gold standard for pharmacological prevention of AMS, and thus HACE is the carbonic anhydrase inhibitor acetazolamide (125–250 mg twice daily). In cases of intolerance or contraindications to acetazolamide, dexamethasone may be taken at a dose of 4 mg twice daily (alternatively, 2 mg four times daily) (Berger et al. 2020b). For detailed dosing recommendations, please refer to the comprehensive description in ► Chap. 7 on AMS.

> It is important that pharmacological prophylaxis should not be used in situations with a low risk of AMS, as this would otherwise limit the options for pharmacological treatment of AMS or HACE.

8.6 Treatment of HACE

HACE is a life-threatening condition. Immediate and "aggressive" treatment is therefore indicated. Individuals who develop HACE at locations with access to a medical facility should be treated with dexamethasone and supplemental oxygen. The aim should be to increase SpO_2 to >90%.

In remote areas without medical care, suspected HACE should prompt immediate descent. This also applies to individuals with severe AMS who deteriorate despite administration of acetazolamide or dexamethasone. If descent is not possible, oxygen should be administered or a portable hyperbaric chamber used. In addition, dexamethasone should be given, with an initial dose of 8 mg (orally, intramuscularly, or intravenously), followed by 4 mg every 6 h (Luks et al. 2024).

There are no systematic data or case reports on re-ascents during the same expedition after resolution of HACE. However, it is recommended to refrain from re-ascending in such situations. If re-ascent is attempted, the individual should at least be asymptomatic and should not have taken dexamethasone for at least 2–3 days prior to re-ascending (Luks et al. 2024). Furthermore, it is strongly recommended to strictly adhere to a conservative ascent rate (▶ Sect. 8.5.1).

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High-Altitude Pulmonary Oedema

Rainald Fischer and Marc Moritz Berger

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As early as 1900, cases of pneumonia and oedema with fatal outcomes were reported among high-altitude mountaineers. One well-known case is that of Dr. Jacottet, who died in a hut just below the summit of Mont Blanc after refusing to descend further during a rescue operation (Mosso 1898). Further reports emerged from South America describing the so-called re-entry pulmonary oedema, primarily affecting high-altitude residents who developed HAPE upon returning to altitude after a stay at lower elevations. The first description in the English-language literature was published by Houston in 1960 (Houston 1960). In subsequent years, it became clear that this condition, previously referred to as pneumonia, was in fact pulmonary oedema that rapidly improved with descent or administration of oxygen. Over the following years, this condition was studied extensively, particularly with regard to its underlying pathophysiology.

High-altitude pulmonary oedema (“HAPE”) is one of the few diseases that can be deliberately induced for research purposes by rapid ascent to high altitude. It resolves quickly and without sequelae following descent and/or pharmacological treatment.

9.1 Case Study

During an organised group expedition to Mustagh Ata (7545 m), a 30-year-old man developed HAPE at base camp at an altitude of 4500 m. The approach involved a bus journey from Islamabad over the Khunjerab Pass (over 4500 m) and a short ascent to base camp, taking a total of 4 days. The day after arrival at base camp, the young man ascended to Camp 1 at over 5000 m. On descent, he noticed reduced physical performance; the descent of 1000 vertical metres took 3 h. His oxygen saturation measured at dinner was approximately 70%, about 10% lower than the group average. During the night, he awoke with cough, shortness of breath, and audible crackles over the lungs. Oxygen saturation had dropped below 60%, and his pulse exceeded 130 beats per minute. Suspecting HAPE, the group was alerted; the mountain guide administered nifedipine 20 mg sustained release, and the patient was placed in a portable hyperbaric chamber (Certec bag). Simulated descent of approximately 2000 vertical metres led to rapid improvement in oxygenation, and after 3 h in the chamber, the patient was able to descend unaided 800 vertical metres to the road. He then travelled by vehicle to Kashgar (1100 m), where he stayed for 2 days. After returning to base camp and resting there for a further 5 days without physical exertion, he was ultimately able to reach the summit of Mustagh Ata without recurrence of HAPE.

9.2 Incidence and Mortality

In a typical mountaineering population, the incidence of HAPE is approximately 0.2% when an altitude of over 4000 m is reached within 3 days (Bärtsch 1997). If this altitude is reached within a single day, the incidence increases to around 7%. It is even higher (over 60%) in individuals with a previous episode of HAPE, indicating an increased individual predisposition to developing this condition. In the mid-altitude regions of the Alps and North America, the prevalence of HAPE among mountaineers and skiers ranges between 0.01% and 0.1% (Hultgren et al. 1996). For the Himalayas and South America, figures vary depending on the population studied, with reported rates between 0.6% and 2.5% (Hultgren and Marticorena 1978).

Women may be somewhat less susceptible to HAPE than men, possibly due to ventilatory stimulation by progesterone and the reduced pulmonary arterial pressure associated with oestrogen (Hultgren et al.

1996; Lahm et al. 2008). In recent years, the overall incidence appears to be declining, mainly due to improved awareness of the condition, leading to earlier recognition and treatment (West et al. 2013).

There are no definitive data on mortality. The estimated mortality rate for individuals with untreated HAPE is 50% (Bärtsch and Swenson 2013). In contrast, rapid and usually complete reversibility is observed following descent and/or pharmacological treatment, which in some cases allows re-ascent without problems after only a few days (West et al. 2013).

9.3 Typical Clinical Presentation

HAPE typically occurs within the first 2–5 days after arrival at altitudes above 3500–4000 m. It is often preceded by intense physical exertion. In approximately 50–70% of cases, symptoms of acute mountain sickness (AMS; see ▶ Chap. 7) are also present.

Clinical Symptoms of High-Altitude Pulmonary edema

Typical warning symptoms include reduced exercise capacity or exertional dyspnoea, cough, and a feeling of chest tightness.

As HAPE progresses, alarm symptoms develop, including severe cough, whitish to reddish frothy sputum, dyspnoea, crackles over the lungs, cyanosis, tachypnoea, and occasionally fever up to 38.5 °C.

Oxygen saturation is usually below 50%, with arterial PaO_2 around 25 mmHg (Bärtsch et al. 1987). As HAPE typically occurs in settings without access to standard medical diagnostics, diagnosis must rely on history, clinical examination, and oxygen saturation. An important differential diagnosis is pulmonary embolism, which usually presents without signs of pulmonary oedema. In pneumonia, fever is higher, and sputum is more likely to be yellow-green. If further diagnostics are available, chest X-ray typically shows patchy infiltrates with some thickening of the pulmonary arteries. Initially, infiltrates are more peripheral, later becoming more homogeneously distributed. Laboratory findings are generally unremarkable except for leukocytosis; a negative D-dimer is important (Khan et al. 2003).

9.4 Predisposing Factors and Physiological Characteristics

There is not a single predisposing factor for HAPE; rather, it results from the interplay of several factors, which are summarised in ▣ Table 9.1.

Pulmonary function analysis in individuals susceptible to HAPE reveals a reduction in total lung capacity by approximately 10–15% and a roughly 30% lower functional residual volume (Steinacker et al. 1998). In addition, a decreased diffusing capacity is observed, which ultimately indicates a reduction in the pulmonary capillary bed. However, it remains unclear whether these findings are causes or consequences of HAPE, as prospective studies are lacking.

Individuals susceptible to HAPE also exhibit a reduced hypoxic ventilatory response, meaning that at a given altitude they have a lower arterial oxygen saturation than control subjects. This is particularly evident during exertion, when HAPE-susceptible individuals show a marked desaturation (Hackett et al. 1988).

As an additional factor, reduced fluid reabsorption from the alveolar space may contribute to the development of HAPE. The reabsorption of fluid from the alveolar space primarily depends on the active transport of sodium (Na^+) and chlo-

Table 9.1 Factors contributing to susceptibility to HAPE

	Factors
Haemodynamics	Exaggerated hypoxic pulmonary vasoconstriction (HPV)
	Exaggerated increases in pulmonary arterial pressure during exercise in normoxia
	Increased sympathetic tone under hypoxia
	Reduced vascular endothelial NO production under hypoxia
	Increased vascular endothelial endothelin production under hypoxia
Pulmonary	Reduced lung volumes
	Limited improvement in lung diffusing capacity under hypoxia and exertion
	Presumed reduced alveolar epithelial sodium and water reabsorption capacity
Ventilation and renal function	Reduced hypoxic ventilatory response (HVR)
	Decreased natriuretic response to acute hypoxia

Adapted from Swenson and Bärtsch (2012)
NO Nitric oxide

ride (Cl^-) by type I and II alveolar epithelial cells (Matthay et al. 2002). Sodium is initially taken up into the cell via various Na^+ transporters located in the apical cell membrane and is then transported out of the cell on the basolateral side by the Na^+/K^+-ATPase. This creates an electrochemical gradient that water passively follows. Water reabsorption probably occurs paracellularly and/or via aquaporins, which are predominantly found on type I alveolar epithelial cells. Fluid is removed from the lung interstitium via the lymphatic vessels, which are presumably less well developed in individuals prone to HAPE (Carter et al. 1997). Hypoxia reduces the expression and activity of the epithelial sodium channel (ENaC) and the Na^+/K^+-ATPase, thereby inhibiting transepithelial Na^+ transport (and thus alveolar fluid reabsorption) (Mairbäurl 2006). However, it remains unclear to what extent reduced alveolar fluid reabsorption and lymphatic transport capacity truly contribute to the pathophysiology of HAPE. It is also conceivable that alveolar Cl^- secretion via the CFTR channel may play a role.

Impaired pulmonary fluid clearance may also lead to a subclinical, interstitial pulmonary oedema. The literature discusses controversially whether this represents a precursor to HAPE or a normal physiological response (Cremona et al. 2002). Current literature suggests this appears to be a normal finding; at the very least, it is difficult to consistently demonstrate subclinical pulmonary oedema (Dehnert et al. 2010).

Increased sympathetic activity may also be of significance in individuals susceptible to HAPE. This has been demonstrated by direct measurements of sympathetic activity and by catecholamine measurements in the blood of individuals prone to HAPE (Duplain et al. 1999; Berger et al. 2011).

Genetic markers for the identification of HAPE candidates have so far yielded no clear results. Investigated were different isoforms of NO synthase, the *VEGF* gene, the

ACE gene, various HLA complexes, and polymorphisms of pulmonary surfactant proteins A1 and A2. However, none of these studies have demonstrated a clear correlation with the occurrence of HAPE (West et al. 2013). This may also be due to the still limited number of subjects studied.

9.5 Pathophysiology

A key feature of HAPE is an excessive rise in pulmonary arterial pressure in hypoxia (Swenson and Bärtsch 2012), which leads to the so-called stress failure of the pulmonary capillaries. In untreated patients with HAPE, mean pulmonary arterial pressures of around 60 mmHg (35–100 mmHg, with normal wedge pressures) have been observed. It has also been shown that not only is there an increase in pulmonary arterial pressure, but also that in the microvasculature (vessels less than 100 μm in diameter) a pressure rise above 20 mmHg occurs (Maggiorini et al. 2001). This also explains why individuals with pulmonary arterial hypertension alone do not develop oedema. This increased pressure in the alveolar microvasculature is probably mainly due to an inhomogeneous, excessive, hypoxic pulmonary vasoconstriction, which in areas of high perfusion leads to increased capillary and pulmonary arterial pressure with leakage of fluid from the pulmonary vessels. An additional rise in pulmonary vascular pressure results from hypoxic venoconstriction.

The underlying cause of the excessive pulmonary arterial pressure increase in individuals susceptible to HAPE is a hypoxia-induced endothelial dysfunction, associated with reduced bioavailability of the vasodilator nitric oxide (NO) as well as increased production of endothelin-1 and oxygen radicals (Berger et al. 2005, 2008; Bailey et al. 2010).

Microscopic evidence of stress failure was provided by West et al. (1995) using in situ perfused rat lungs at a simulated altitude of approximately 8800 m. This resulted not only in exudation of high-molecular-weight proteins and cells, but also of erythrocytes.

An interesting and clinically relevant observation during an episode of HAPE is that breaks in the alveolocapillary membrane are rapidly reversible when blood pressure in the pulmonary vessels is reduced. This occurs within just a few minutes (Elliott et al. 1992). This rapid repair may also play a role in the fact that HAPE does not usually occur after the first 5 days at a given altitude. It is possible that there is also rapid remodelling and generalised muscular hypertrophy of the pulmonary arterioles, leading to a more uniform pressure across all pulmonary vessels and thus to vascular stabilisation.

For a long time, it was debated whether infection might be the trigger for HAPE. It now appears clear that inflammation contributes at most secondarily to the progression of pulmonary oedema (Swenson et al. 2002). Only interleukin-6 (IL-6) has been detected at an early stage, but this may also be due solely to physical exertion. It is possible that IL-6 is simply a marker of physical activity and hypoxia, and thus not a classical marker of inflammation.

9.6 Prevention of High-Altitude Pulmonary Oedema

Analogous to the prevention of acute mountain sickness (see ▶ Chap. 7) and high-altitude cerebral oedema (see ▶ Chap. 8), the best prevention is a slow ascent to altitudes above 3000 m and good pre-acclimatisation. In this context, reference should also be made to the chapter on acclimatisation (see ▶ Chap. 6). Particularly important, however, is the avoidance of strenuous physical activity upon arrival at a new altitude, to minimise the hypoxia-induced, excessive rise in pulmonary arterial pressure. This is especially relevant for those prone to developing HAPE. For pharmacological prophylaxis, it has been shown that 20 mg of sustained-release nifedipine three times daily effectively prevents HAPE in HAPE-susceptible individuals (Bärtsch et al. 1991).

In recent years, the carbonic anhydrase inhibitor acetazolamide has increasingly come into focus (Swenson 2014). This medication is considered the gold standard for the prevention of acute mountain sickness. In a randomised, placebo-controlled double-blind study, it was investigated whether acetazolamide reduces the extent of altitude-induced pulmonary arterial hypertension and prevents HAPE during rapid ascent to 4559 m. The results showed no statistically significant differences in the incidence of HAPE between the acetazolamide and placebo groups. There was also no difference in the level of pulmonary arterial pressure. However, acetazolamide reduced the incidence and severity of acute mountain sickness and improved blood oxygen saturation. Therefore, acetazolamide cannot be recommended for the prevention of HAPE (Berger et al. 2022). For the prophylaxis of acute mountain sickness, however, it remains the first line medication.

Other prophylactic medications may include dexamethasone and phosphodiesterase inhibitors. It has been shown that dexamethasone at a dose of 3 × 8 mg per day is equally effective in lowering pulmonary arterial pressure as tadalafil (Maggiorini et al. 2006). Possible explanations for this effect include stimulation of NO production, reduction of pulmonary vascular sympathetic tone, improved alveolar fluid reabsorption, and enhanced surfactant secretion. However, oral dexamethasone was only effective if administered sufficiently early. Late prophylaxis (1 day after arrival at altitude) was less effective (Maggiorini et al. 2009). There is, however, a report of a reduction in pulmonary arterial pressure in a child 2 h after administration of dexamethasone (Kriemler et al. 2006). For tadalafil, sildenafil, and vardenafil, it has been demonstrated that pulmonary arterial pressure can be reduced in both normoxia and hypoxia after acute exposure and after acclimatisation. In addition, administration of phosphodiesterase inhibitors appears to improve exercise capacity compared to placebo (Richalet et al. 2005). However, it should be noted that there may be both responders and non-responders. Other pulmonary arterial pressure-lowering agents such as inhaled NO, ambrisentan, minoxidil, or lovastatin have not yet been sufficiently studied, but are presumably also effective.

9.7 Treatment of High-Altitude Pulmonary Oedema

There are no controlled studies on the treatment of HAPE, in contrast to its prevention. Nevertheless, a pragmatic approach has become established (Swenson et al. 2002). In mild to moderately severe cases of HAPE when medical care is available, such as in a high-altitude ski resort with access to oxygen, it is acceptable to maintain oxygen saturation above 90% and to monitor the course of the illness.

In all other cases, the decisive treatment for HAPE is immediate and prompt descent. A descent of just 300–500 m can lead to a marked improvement in the clinical picture. In addition, administration of oxygen is highly effective, although often limited in duration due to restricted availability.

On trekking tours or expeditions, the portable hyperbaric chamber has become established as a therapeutic option (Certec-Bag, Gamow-Bag). These are inflatable bags that can be pressurised to about 200 mbar, equivalent to a descent of approximately

2000 m. The optimal duration of therapy in the hyperbaric chamber is unclear, but at least 1–2 h are probably necessary.

Pharmacologically, pulmonary arterial pressure can be reduced with nifedipine 20 mg sustained release (three times daily); sildenafil (50 mg) or tadalafil (20 mg) are presumably also effective (Luks et al. 2019). Oral administration of dexamethasone (8 mg) is not harmful, but it is unclear whether it is effective in established HAPE. The efficacy of inhaled NO donors and inhaled prostacyclin analogues has not yet been tested (Swenson et al. 2002).

Diuretics are not recommended, as they do not affect the pathomechanism and most patients with HAPE are dehydrated. Antibiotic therapy is not indicated unless there is a concomitant infection of the upper or lower respiratory tract.

Due to improved awareness and the availability of various preparations, multimodal therapy is now frequently used in HAPE. However, controlled studies are lacking to demonstrate that the use of different pulmonary arterial pressure-lowering agents is more effective than, for example, nifedipine alone.

Conclusion

The key pathophysiological feature of HAPE is excessive hypoxic pulmonary vasoconstriction. The main symptoms at the onset of HAPE are reduced exercise tolerance and cough. The most effective measures for preventing high-altitude pulmonary oedema are slow ascent, adequate pre-acclimatisation, and minimising physical exertion during the first 3–5 days at a new altitude. The primary therapeutic interventions for HAPE are descent, administration of oxygen, use of a portable hyperbaric chamber, and pharmacological treatment with nifedipine 20 mg sustained release three times daily (alternatively, sildenafil 50 mg).

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Pulse Oximetry at High Altitude

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10.1 Pulse Oximetry at High Altitude

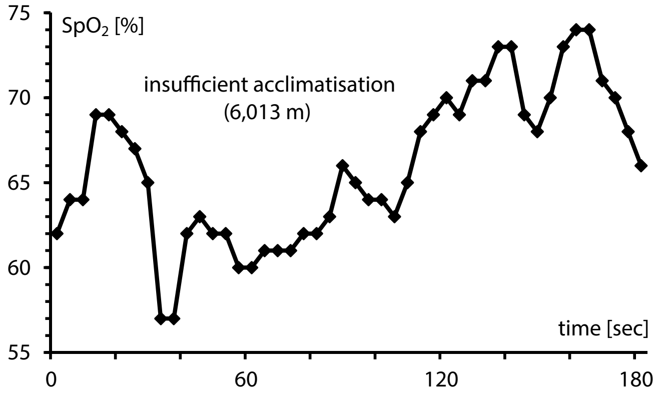
During high-altitude mountaineering and trekking, it is common practice to determine oxygen saturation (SaO_2) using pulse oximetry (SpO_2). This is frequently used in the diagnosis of acute mountain sickness (AMS) or to help assess the degree of acclimatisation (Basnyat 2014; Luks and Swenson 2011; Mandolesi et al. 2014; Roach et al. 1998; Saito et al. 1995; Tannheimer et al. 2002). However, these measurements are much more complex and prone to error at high altitude than at sea level (Luks and Swenson 2011; Tannheimer and Lechner 2019; Windsor 2012; Windsor and Rodway 2014), which is why pulse oximetry is viewed critically by experts in this context (Bärtsch 2005; Basnyat 2014; Luks and Swenson 2011; Windsor and Rodway 2014). There are also no standard reference values, as these vary depending on altitude and acclimatisation status, and there is considerable inter-individual variability. For example, the author is among those who regularly exhibit lower SpO_2 values in group comparisons, without being more susceptible to AMS. The following section describes the specific aspects of pulse oximeter measurements at high altitude and provides recommendations for their implementation.

There is consensus regarding the use of pulse oximetry for monitoring ill or injured individuals at high altitude (Bärtsch 2005; Luks and Swenson 2011; Tannheimer et al. 2009a, b). Concerns exist regarding potential sources of error due to cold-induced circulatory disturbances or movement artefacts (Kamat 2002; Lee et al. 2004; Luks and Swenson 2011). In our view, movement artefacts are fundamentally incompatible with the defined conditions of a resting measurement. The subject should be seated calmly, wearing warm clothing with warm fingers, the sensor protected from sunlight, while an experienced examiner visually determines the representative mean value from a 2- to 3-min measurement interval (Luks and Swenson 2011; Mandolesi et al. 2014; Tannheimer and Lechner 2019). If the measurement is disrupted by movement, it is discarded and simply repeated after standardising and optimising the measurement conditions. If the measurement finger is too cold and if no signal can be obtained, the finger must first be warmed up, for example, in the armpit. If hyperventilation has not occurred, a resting oxygen saturation >90% generally rules out AMS. Alarmingly low values compared to the group or over time in an individual are cause for targeted questioning and closer monitoring. At high altitudes, oxygen saturation can sometimes drop significantly. In mountaineers on Mount Everest (8400 m: via puncture of the femoral artery), values for paO_2 as low as 19.1 mmHg and for SaO_2 as low as 34.4% have been recorded (Grocott et al. 2009). These values are far below the measurement range for which pulse oximeters are designed. Therefore, some authors have highlighted the potential inaccuracy of pulse oximeters in the low saturation range <75% (Luks and Swenson 2011; Windsor and Rodway 2014). However, systematic studies have shown only a deviation of 1.8% down to an SpO_2 value of 57% (Benoit et al. 1997). Earlier studies have demonstrated relatively good agreement in dogs in the saturation range between 22% and 100%: $R^2 = 0.97$ (Sendak et al. 1988), in children in the range of 35–95%: $R^2 = 0.90$ (Boxer et al. 1987), and also in children in the range of 30–80%: $R^2 = 0.94$ (Lazzell and Jopling 1987). For the pulse oximeter, we use most frequently (Palm-Sat 2500®) Nonin® specifies a constant accuracy of ±2 percentage points in the saturation range of 70–100% (Nonin Medical Inc. 2010). In 14 intensive care patients, we compared pulse oximeter with arterial SaO_2 in the saturation range of 45–98% and found an excellent correlation of R^2: 0.99 ($p < 0.001$) (Tannheimer et al. 2002).

10.2 Circadian Rhythm and Periodic Breathing Influence Oxygen Saturation

As SaO_2 values are subject to a circadian rhythm, the timing of measurement is crucial for the assessment and comparability of SpO_2 values (Tannheimer et al. 2017). The highest SpO_2 values are found in the morning. These decrease over the course of the day and rise again during the night, so that values in the first half of the night are normally lower than those in the second half (Tannheimer et al. 2017, 2018a, b). This circadian rhythm, with nocturnal minima, appears to be the normal physiological pattern of SaO_2, both during the ongoing acclimatisation process and in long-term residents at high altitude (Cristancho et al. 2016; Pomidori et al. 2009; Tannheimer et al. 2017). From a physiological perspective, this nocturnal drop in SaO_2 is of great significance as a stimulus for erythropoietin (EPO) secretion and thus for maintaining an elevated haematocrit, even after acclimatisation has occurred (Böning et al. 2018; Tannheimer et al. 2010, 2018a, b). A disturbed nocturnal saturation pattern may be an early indicator of impaired acclimatisation (Tannheimer et al. 2017).

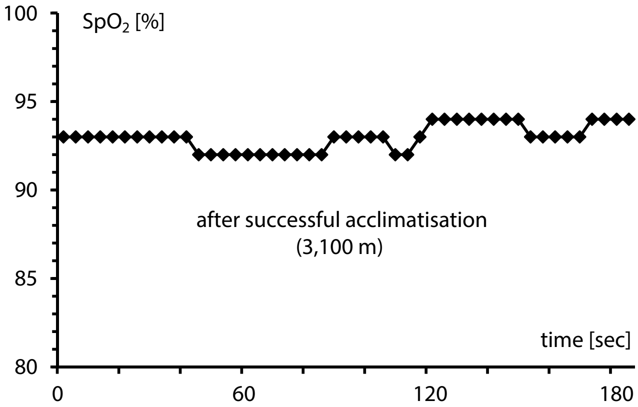
Due to the typical periodic breathing at high altitude, SpO_2 values fluctuate considerably, making it difficult to determine an accurate measurement value (Küpper et al. 2008; Tannheimer and Lechner 2019; West et al. 1986). We were able to demonstrate fluctuations in SpO_2 values at rest (6013 m) of 17 percentage points (57–74%) within a measurement interval of only 3 min (■ Fig. 10.1) (Tannheimer and Lechner 2019). In order to determine an accurate mean value, measurements must therefore be conducted over a sufficiently long period in order to reflect the average blood oxygen content that is critical for the organism at high altitude (Küpper et al. 2008; Muza 2018; Pomidori et al. 2009; Tannheimer and Lechner 2019). Isolated single measurements or the use of the highest or lowest SpO_2 value within a measurement interval are therefore unrepresentative and provide no useful information about the actual oxygen supply to the organism (Luks and Swenson 2011; O'Connor et al. 2004; Windsor and Rodway 2014). Insufficient standardisation of SpO_2 measurement at high altitude and fundamental differences in study design are most likely the main reasons for the heterogeneous study conclusions regarding the predictability of AMS



■ **Fig. 10.1** Cyclical saturation pattern with insufficient acclimatisation. The difference between the maximum and minimum values within the measurement interval is 17 percentage points by pulse oximetry (Chen et al. 2012; Karinen et al. 2010; O'Connor et al. 2004; Roeggla et al. 1996; Saito et al. 1995; Tannheimer and Lechner 2019; Wagner et al. 2012).

10.3 Conducting Pulse Oximeter Measurements at Altitude

Based on extensive experience with SpO_2 measurements up to an altitude of 7100 m (Tannheimer et al. 2002, 2009a, b, 2013, 2017; Tannheimer and Lechner 2019), we consider a strictly standardised and identical determination of SpO_2 at rest to be an essential prerequisite for its application in high-altitude medicine (Bärtsch 2005; Tannheimer and Lechner 2019; Windsor 2012). The measurement should always be performed at the same time of day, usually in the morning, in a fasting state (Tannheimer et al. 2017, 2018a, b). When measuring, it is necessary to calculate a representative mean value over a sufficiently long measurement interval (Luks and Swenson 2011; Mandolesi et al. 2014; Tannheimer and Lechner 2019). We recommend that this measurement interval should cover at least three periods of periodic breathing, corresponding to a measurement duration of 2–3 min (Tannheimer and Lechner 2019; Tannheimer et al. 2002). This represents a significant time investment when a large group of mountaineers is measured every morning. With improved acclimatisation, the range of fluctuation of the SpO_2 cycles decreases, and the determination of the representative SpO_2 value becomes easier, sometimes just as easy as at sea level (see ◘ Figs. 10.1 and 10.2). In such cases, the measurement interval can be shortened (Tannheimer and Lechner 2019). For pulse oximetry measurements at high altitude, the examiner requires experience, as the representative SpO_2 value for the measurement interval must be determined visually based on the values displayed on the device (Tannheimer and Lechner 2019). Even experienced examiners tend to overestimate this representative SpO_2 value, especially when measuring their own value (Tannheimer and Lechner 2019). If pulse oximetry is performed in the standardised manner described and the generally accepted definition of AMS and its latency period of 6–36 h until onset of the disease are taken into account in the study design (Hackett and Roach 2001; Luks et al. 2017; Muza 2007; West 2012), determination of SpO_2



◘ **Fig. 10.2** Saturation profile in an acclimatised state in the same individual as in ◘ Fig. 10.1, 2 days later and almost 3000 m lower. The measurement could be performed over a shorter period similar to sea level allows prediction of AMS (Basnyat 2014; Karinen et al. 2010; Roach et al. 1998; Tannheimer et al. 2002).

Endurance athletes sometimes show inappropriately low resting SpO_2 values in pulse oximetry. If conspicuously low resting SpO_2 values do not fit the clinical picture, the individual should perform light physical activity (e.g. walking around or five 5 squats) and then measurements taken again (Saito et al. 1995; Tannheimer et al. 2009a, b). If the measured value is then higher, this value is used (Tannheimer et al. 2009a, b). Such a finding is indicative of adequate acclimatisation. However, if SpO_2 falls further during this moderate physical exertion, this is a warning sign of (as yet unapparent) high-altitude illness, and clinical assessment of health status, possibly with re-evaluation over time, is recommended.

A significant source of error in determining SpO_2 at high altitude is due to hyperventilation (Tannheimer et al. 2009a, b), which often occurs either intentionally or unintentionally in the subjects studied (Tannheimer et al. 2009a, b; Tannheimer and Lechner 2019). This significantly distorts the SpO_2 measurement, so the examiner must always be alert to hyperventilation. To aid measurement accuracy, it may be helpful if the subject cannot see the device display. Conversely, a lack of significant increase in SpO_2 during hyperventilation indicates impaired alveolo-capillary diffusion. If an individual shows a significantly low SpO_2 compared to the group or their own previous measurements, and this does not increase markedly with deliberate hyperventilation (e.g. from 65% to >75%), this is highly suspicious for incipient HAPE (Tannheimer et al. 2009a, b).

> Hyperventilation is the most significant source of error in pulse oximetry measurements at altitude.

The influence of hyperventilation is reduced in measurements during physical exertion. However, movement artefacts may also impair measurement accuracy (Kamat 2002; Lee et al. 2004), although this influence is less significant than previously assumed. For example, during an ice climb using ice tools (Les Courtes, 3856 m via the NE couloir: 800 m, 45–50° steep ice), a sufficient number of correct SpO_2 readings could still be obtained from finger measurements to allow a meaningful assessment of the saturation trend (Tannheimer et al. 2018a). We were also able to demonstrate that a test scenario in which the time required for an uphill sprint and the lowest SpO_2 value measured during the effort are used, enabled assessment of individual acclimatisation status as well as risk estimation for susceptibility to AMS at higher altitudes (Tannheimer et al. 2009a, b, 2013). For daily high-altitude medical practice, however, measurement at rest is of greatest relevance, while measurements during sleep or physical exertion can provide valuable additional information.

Conclusion

Pulse oximetry is regularly used by non-medical individuals during stays at high altitude. Its value for monitoring and therapeutic supervision of ill and injured patients is undisputed. In addition to clinical examination, it is an important tool for the early detection of altitude illness and assists in assessing individual acclimatisation status. For this assessment, the individual's trend over time and the SpO_2 values within each group with a similar acclimatisation profile serve as reference points, whereby inter-individual variability should be considered. Pulse oximetry at altitude is considerably more complex than at sea level and requires an experienced examiner both for determining the actual measurement value and for its interpretation and the resulting recommendations. The inclusion of altitude history, clinical examination, and mountaineering aspects generally requires a physician with experience in high-altitude medicine.

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Pre-acclimatisation

Martin Faulhaber, Maria Wille, and Hannes Gatterer

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Exposure to altitude without adequate acclimatisation is associated with the risk of altitude illnesses and reduced endurance performance. In certain situations, pre-acclimatisation may be helpful in minimising these adverse effects.

When ascending to altitudes above 2500 m, the human body must adapt to the altitude-related relative oxygen deficiency. Failure to do so can result in various forms of altitude illness, of which acute mountain sickness (AMS) is the most common (Bärtsch and Swenson 2013). The prevalence of AMS increases with altitude (Mairer et al. 2009; Wille et al. 2007; Maggiorini et al. 1990), and individuals who ascend rapidly to high altitude and with fewer days of acclimatisation are more likely to develop AMS (Bärtsch and Swenson 2013; Schneider et al. 2002; Maggiorini et al. 1990). In practice, the recommendations for classical acclimatisation to prevent altitude illness are often difficult to follow due to the need for rapid hut approaches and cable car ascents, adverse weather conditions, shortened tour durations, and time constraints. In such cases, pre-acclimatisation may serve as an alternative or at least a supplement to classical on-site acclimatisation, particularly for AMS-susceptible individuals.

11.1 Pre-acclimatisation at Natural Altitude

Even a stay of several days at altitudes of around 2000 m results in moderate physiological adaptations and is likely to lead to effective pre-acclimatisation. It has been shown that after a 6-day stay at 2200 m, the prevalence of AMS during subsequent acute exposure to 4300 m was reduced by approximately 50% (Beidleman et al. 2009). Furthermore, studies have demonstrated that prior short-term stays at natural altitude (repeated daytime exposures) as a form of pre-acclimatisation can reduce the risk of AMS (Schneider et al. 2002; Weng et al. 2013). Thus, these strategies of pre-acclimatisation at natural altitude may be helpful in preventing the development of AMS.

11.2 Pre-acclimatisation in Simulated Altitude

Researchers began early on to simulate the acclimatisation strategies of mountaineers—repeated ascents and descents between camps—in altitude chambers (hypoxic chambers) (Nagasaka and Satake 1969; Richalet et al. 1992). These early studies, which involved very time-intensive and extensive hypoxic exposures, proved to be suitable preparation for subsequent stays at altitude (Burtscher 2005). In an early study by Richalet et al. (1992), the acclimatisation period on Mount Everest could be reduced by 1–3 weeks. In recent years, these pre-acclimatisation strategies have gained increasing importance in commercial expeditions to the world's highest mountains. These so-called flash expeditions combine several weeks of pre-acclimatisation at home with the use of supplemental oxygen during the summit push. Compared to traditional expeditions, this type of expedition requires roughly half the travel time, and providers report very high success rates when applying this strategy (Tannheimer and Lechner 2020). However, this form of pre-acclimatisation is likely to remain reserved for expeditions to extreme altitudes due to the considerable time and financial investment involved.

Of particular interest for mountaineering outside of extreme expeditions is the fact that repeated hypoxic exposures lasting from one to several hours can induce acclimatisation effects. These include increased ventilation and improved arterial oxygen saturation both at rest and during exercise (Burtscher et al. 2008; Beidleman et al. 2003; Jones et al. 2006; Katayama et al. 2001; Katayama

2009). Thus, such pre-acclimatisation protocols could improve performance at altitude and additionally minimise the risk of altitude illnesses and therefore represent a time- and cost-effective alternative to continuous stays in the mountains. However, there is a wide variety of pre-acclimatisation protocols in the literature with no standardised approach.

To date there are only a few mainly uncontrolled studies that have investigated the potentially positive effects of repeated hypoxic exposures for the prevention of AMS. The available results indicate that repeated stays in a hypoxic chamber can influence the development of AMS. In particular, hypoxic exposures of ≥3 h per day over several days (Fulco et al. 2011; Muza et al. 2006; Kolb et al. 2004) for up to several weeks (Dehnert et al. 2009; Beidleman et al. 2004) or hypoxic exposures of >1 h per day over 4 weeks (Schommer et al. 2010) have demonstrated a reduction in AMS incidence or at least reduced AMS symptoms. Therefore, (almost) daily exposures of 1–3 h at a simulated altitude of >4000 m, carried out over at least 1 week, are likely to represent the minimum requirement for successful pre-acclimatisation (Burtscher et al. 2008).

It should be noted, however, that those studies showing a significant reduction in AMS were neither blinded nor placebo-controlled (Beidleman et al. 2004; Kolb et al. 2004; Muza et al. 2006) and the results must be interpreted with caution. Studies employing a blinded, placebo-controlled design showed only a partial reduction in AMS incidence (Schommer et al. 2010; Fulco et al. 2011) or AMS severity (Wille et al. 2012). For example, Schommer et al. (2010) were able to demonstrate a reduced AMS incidence at 3611 m after pre-acclimatisation, but not at 4559 m, and in the study by Fulco et al. (2011), AMS symptoms were only temporarily reduced. In a laboratory study at the University of Innsbruck, pre-acclimatisation (seven 1-h passive exposures on seven consecutive days at a simulated altitude of 4500 m) was shown to reduce AMS severity (Wille et al. 2012). However, the same pre-acclimatisation protocol in a subsequent study with AMS-susceptible individuals did not have a preventive effect on AMS during a subsequent acute exposure at 3650 m in natural altitude (Faulhaber et al. 2016). Thus, the effectiveness of highly time-efficient pre-acclimatisation strategies (e.g. repeated one-hour hypoxic exposures) is questionable. A review published in 2022 also concluded that pre-acclimatisation protocols with a total exposure duration of more than 60 h should be used to achieve reliable effects (Burtscher et al. 2022). The available scientific studies do not allow a definitive conclusion for this topic. However, individuals with a very low hypoxic ventilatory response, often found in individuals susceptible to high-altitude pulmonary oedema, could benefit from these protocols (Burtscher et al. 2008). Nevertheless, specific study results for this target group are not yet available.

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12

Preventive Medicine and Health Tourism Aspects of Moderate Altitudes

Beatrix Schobersberger and Wolfgang Schobersberger

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The fascination that mountains engender is not solely rooted in athletic achievement. Mountains can encourage existential reflection and thus also provide spiritual feelings. Since the dawn of humanity, mountains have played a central role in world religions, providing a connection between heaven and earth. For local populations, mountains were both dangerous and captivating, and were only used when necessary.

It was only through scientific exploration and the construction of trade routes that the Alps were gradually appropriated as a living space. Not only has travel become a mass phenomenon, but “mountain travel” (as it was called around 1800) has also become “democratised”, becoming accessible to many people.

The once forbidding and inaccessible Alps have been developed in many ways. Trails have been marked; hotels, huts, and bivouacs serve as practical bases; transport enables speedy access to starting points; modern rescue services, advances in medical technology, and comprehensive insurance systems allay fears. Two centuries of accumulated mountaineering experience now provide a wealth of benefits. At the dawn of alpinism, it was not clear what awaited people on the highest peaks, nor how their bodies would respond to altitude (Scharfe 2007).

During the enlightenment, the idea emerged that mountains could be paradisiacal places, as glorified by Albrecht von Haller in his 1729 poem “The Alps”. The culmination of this development is the use of mountains for tourism and recreation, whether as a space for athletic challenge or for contemplative introspection (Steinbach-Tarnutzer 2011). In parallel with the discovery of mountains as spaces for recreation and economic activity, “altitude medicine” has developed as a distinct scientific discipline over the past century.

A pioneering model for the health benefits of moderate altitude is the so-called climate therapy in the Swiss health resort of Davos. Alexander Spengler, a newly qualified 26-year-old physician, took up his first post in 1856 in the remote community of Davos, Switzerland, at 1560 m above sea level. Neither he nor the citizens of Davos could have foreseen that his work would bring Davos worldwide renown. Skin diseases (atopic skin disorders) and respiratory diseases (including tuberculosis and allergic asthma) were successfully treated in the newly established clinics and sanatoria (Bruck 2004), marking the beginning of the medical era of alpine climate therapy.

In simplified terms, climate therapy refers to a specialised medical treatment that takes advantage of the beneficial effects of a particular climatic environment, such as the sea or altitude (Schuh 2004). In the Alpine region, these favourable climatic factors include moderate hypoxia, fluctuating temperatures, wind, high light exposure with increased UV radiation, dry air, and low allergen levels.

Whereas several decades ago climate therapy was mainly used as an adjunct treatment for tuberculosis and reached its peak in the 20th century in conjunction with spa and rehabilitation stays, a new branch of the health sector has since developed: health tourism. Health tourism is a form of tourism in which travel is combined with visits to health destinations, where the primary purpose of the trip is to enhance physical well-being through a combination of physical activity, dietary measures, and medical services aimed at maintaining health (modified after UNWTO in Gee and Fayos-Sola 1997).

Health tourism as a part of mountain tourism is predominantly found in the Alpine region of Europe. More than 13 million people inhabit the 191,000 km^2 Alpine arc, which spans seven countries and comprises a total of 6200 municipalities. The Alps are not only the largest and highest mountain range in Europe but are also highly developed for tourism. As early as the 19th century, the English coined the term “playground of Europe” for the Alps. Mountain tourism in all its facets makes a significant contribution to the development of rural areas. Many higher-altitude regions and valleys would probably no longer be inhabited today without the creation of jobs in the leisure and tourism sector. The intense tourism pressure on the natural environment of the Alps is reflected in extremely high visitor numbers (annual figures; Reiner 2007):

- 4.7 million beds, occupancy rate approx. 25%
- 60 million arrivals per year as well as approx. 60 million day visitors
- 370 million overnight stays
- 50 million visitors
- 20 million skiers
- 5–10 million hikers
- 3 million mountain bikers
- 500,000 climbers
- 120,000 hang gliders
- 100,000 ski tourers

These figures indicate, on the one hand, the economic benefits in terms of tourism, and on the other, the ecological burden on the natural and living environment with all its consequences. Recent studies highlight the significance of tourist overnight stays in the Alpine region, which amounted to approximately 546 million in 2022 (▶ www.de.statistica.com 2023).

The aim of this chapter is to critically examine the Alpine regions, with a focus on the so-called moderate altitudes (1500–3000 m) from a preventive medicine and health tourism perspective.

12.1 Physiology of Moderate Altitudes

Regardless of the generally very similar classifications of different altitude levels (moderate—high—extreme altitude), the term "moderate altitude" (also referred to as "medium altitude") is defined in German-speaking countries as an absolute altitude between 1500 and 3000 m. This classification is based on the fact that up to 3000 m, full acclimatisation of the body to moderate hypoxia is rapidly achievable and that therefore severe forms of acute mountain sickness are extremely rare.

This classification is also highly suitable for health tourism purposes, as the altitudes critical for acclimatisation during an Alpine health holiday fall within the moderate altitude range, and the classic Alpine tourism centres are located no higher than 2000 m.

The following are the physiological parameters of acute adaptation and acclimatisation to moderate altitudes:

- Initial moderate decrease in blood oxygen saturation, with improvement following acclimatisation
- Moderate hyperventilation at rest and during physical exertion
- Initial moderate respiratory alkalosis, which is fully metabolically compensated after a few hours
- Moderate activation of the sympathetic nervous system with only an initial increase in resting heart rate and a variable, slight rise in blood pressure, with both parameters normalising after a short period (maximum 2–4 days)
- No change in resting cardiac stroke volume, and minimal changes in stroke volume during physical activity compared to normoxia
- Rapid stimulation of erythropoiesis with an increase in circulating erythrocyte volume and haemoglobin mass from about 2 weeks of altitude exposure, without clinically relevant polycythaemia
- Moderate reduction in maximal physical performance <5% compared to low altitude

> From a physiological perspective, moderate altitudes offer health seekers the advantage that acclimatisation to altitude is possible even with only moderate hypoxia, and this process is usually completed within a few days.

12.2 Health Risks Associated with Mountain Sports at Moderate Altitudes

Upon sudden arrival at these altitudes, the unacclimatised body responds to even a moderate reduction in inspiratory oxygen partial pressure with a variety of adaptive mechanisms, all aimed at maintaining oxygen supply both at rest and during physical exertion. For certain chronic conditions within the cardiovascular and respiratory spectrum, moderate altitude is generally considered medically safe. However, individual tolerance to altitude appears to vary depending on age, sex, health status, and pre-existing conditions.

12.2.1 Cardiovascular Events During Mountain Hiking and Alpine Skiing

Acute exposure to altitude combined with excessive exercise intensity and unfamiliar environmental conditions such as cold can lead to sudden and severe health impairments. Burtscher et al. (2007) recorded and analysed all fatalities that occurred during mountain hiking in the Austrian Alps over a 9-year period. He reported a mortality rate of 4 per 100,000 mountain hikers, with 50% of these deaths due to sudden cardiac death (SCD), defined as an unexpected, non-traumatic death occurring within 1 h of the onset of cardiac symptoms.

Sudden cardiac death is thus the most common non-traumatic cause of death in the mountains, with 90% of cases occurring in men over the age of 34. The risk increases with advancing age and the presence of cardiovascular risk factors or pre-existing conditions such as previous myocardial infarction, diabetes mellitus, coronary artery disease, arterial hypertension, and hypercholesterolaemia. Additional risk factors include a positive family history and reduced physical fitness due to insufficient engagement in mountain sports prior to the visit to moderate altitude.

A history of myocardial infarction increases the risk of SCD during mountain hiking 11-fold. In comparison, Burtscher et al. (2000) also analysed the SCD rate during alpine skiing and found a mortality rate of 1 per 100,000 skiers per year, with 40% of deaths classified as SCD. The risk profile for SCD during skiing appears similar to that for mountain hiking, although a different pathophysiological mechanism may underlie SCD in skiing compared to hiking. Skiing primarily involves short-term, high-intensity static-dynamic exertion lasting several minutes, whereas mountain hiking is a prolonged, cyclical activity usually performed below the anaerobic threshold. Distinct environmental factors such as cold and terrain play a significant role in this context.

In a questionnaire-based study involving 1431 hikers and 1043 skiers, a research group from Innsbruck demonstrated that the prevalence of one or more cardiovascular risk factors increases from the age of 40 onwards, even among these physically active individuals, regardless of sex or type of sport. The surveyed skiers and hikers with cardiac risk factors reported being physically active for less than 1 h per week (Faulhaber et al. 2007).

All earlier studies on SCD during skiing and mountain hiking were confirmed by the analysis of a larger study cohort. A previous myocardial infarction in both sports and a lack of high-intensity preparatory training among skiers or evidence of metabolic disorders such as hypercholesterolaemia among hikers were identified as the main risk factors (Niebauer and Burtscher 2021).

These findings are consistent with an interesting retrospective analysis investigating a possible association between winter sports participation and the occurrence of myocardial infarction. All heart attack patients admitted to Innsbruck University Hospital during the winter months between

2006 and 2010 were included in the evaluation. In total, 110 patients were included, and the majority of whom were tourists from Germany and the Netherlands.

The main finding of the study was that 56% of all heart attacks occurred within the first 3 days after arrival, while only 22% of cases occurred after the fifth day. The absolute altitude at which heart attack symptoms occurred was around 1500 m. Seventy percent of those affected reported more than two classic risk factors for a cardiovascular event, and over half engaged in less than 2.5 h of sport per week at home. Also, 23% of skiing holidaymakers reported having experienced ischaemic symptoms prior to their trip. The fact that travel-related stress itself may influence the risk of myocardial infarction has also been demonstrated for summer holidays in a study conducted by the Royal Dutch Touring Club in Denmark. Like winter holidays, 21% of heart attacks occurred within the first 48 h after arrival. As a conclusion, it was recommended to minimise both physical and emotional stress at the start of the holiday (Kop et al. 2003).

In another study that included skiers, all cases of type A aortic dissection presenting to Innsbruck University Hospital between 2001 and 2011 were recorded and analysed with regard to potential triggering factors (Schachner et al. 2013). The results showed that 22.1% (17/77) of patients experienced aortic dissection associated with alpine skiing. In 14 of the 17 affected individuals, the dissection occurred non-traumatically while skiing at altitudes between 1200 and 3100 m. In addition to the causes listed below, possible mechanisms discussed include mechanical strain in the form of increased intrathoracic pressure and shear forces acting on the thoracic vascular system, which depends on the skiing technique used.

The following points are discussed as pathophysiological causes and mechanisms for the occurrence of acute cardiovascular events at moderate altitude:

- The unfamiliar type of physical exertion, depending on skiing technique and slope conditions (▶ Sect. 12.2.2).
- Acute exposure to altitude with a lack of acclimatisation in the first few days.
- Unusually cold temperatures. Several studies have shown that both cold and heat exposures increase the risk of acute myocardial infarction, and, in individuals with pre-existing cardiovascular disease who are not acclimatised to the climate, may even increase mortality risk (Madrigano et al. 2013; Medina-Ramon and Schwartz 2007).
- Work-related stress prior to departure as well as travel-related stress itself.
- Pre-existing cardiovascular risk factors.
- Lack of physical activity.

> Proper travel preparation and a journey to the alpine destination with as little stress as possible are crucial for a health-oriented alpine holiday.

12.2.2 Alpine Skiing and Ski Mountaineering from a Sports Medicine Perspective

Should the above findings lead to a general recommendation against taking a mountain holiday, or can the risk of a cardiovascular event at altitude be minimised through appropriate behaviour? From a sports medicine perspective, the metabolic demands of alpine skiing depend on various factors. These include environmental factors: slope conditions such as course profile, snow conditions, and length of run; and personal factors: skiing ability and individual fitness.

The chosen skiing technique, whether carving or parallel turns, the time of day, and age also influence the physical demands of skiing. In the Salzburg Ski Study

(Scheiber et al. 2009), the metabolic demands of alpine skiing were investigated under different conditions (speed, time of day, slope gradient, etc.). The results regarding heart rate and blood pressure response, lactate increase, and oxygen uptake indicated that the metabolic demands of recreational skiing ranged from moderate to high intensity.

In a follow-up study (Niederseer et al. 2011), the long-term effects of alpine skiing on health-related parameters in older individuals (mean age 67 years) were examined over a 12-week observation period with a total of 28 ski days. None of the participants experienced a health event during the 795 h of skiing. The results also showed positive effects on lipid and glucose metabolism as well as a reduction in body fat mass. From a training perspective, improvements in maximal oxygen uptake and muscle strength were observed, indicating a positive training effect.

In summary, the above studies suggest that individuals with pre-existing cardiovascular conditions should pay particular attention to key aspects when embarking on a holiday at altitude in order to reduce their subjective risk of potential cardiovascular events. These include minimising stress before and during travel, acclimatising to altitude and ambient temperature with an initially moderate start to physical activity, and, as generally recommended in preventive medicine, regular training at home and reduction of cardiovascular risk factors.

In recent years, ski mountaineering has developed not only as an alternative or supplement to skiing on prepared slopes for highly trained athletes, but also for many recreational sports enthusiasts. The associated muscular and cardiopulmonary strain profile is characterised by the combination of ascent and descent, that is, a combination of concentric and eccentric loading of the lower limb muscles, as well as highly variable cardiovascular stress (both anaerobic and aerobic components). Initial studies have demonstrated that ski mountaineering may also have potential for health tourism in the future (Haslinger et al. 2018).

A sports medicine assessment is recommended for individuals with a pre-existing high cardiovascular risk profile, but it should also be considered as benefit for the optimisation for all winter sports in healthy individuals. In addition to classic alpine skiing, snowshoeing and ski touring are enjoying increasing popularity. When performed correctly (e.g. not too fast and not at excessive altitude), both forms of exercise are highly suitable from a preventive medicine and training methodology perspective for achieving health benefits (Burtscher et al. 2018).

12.3 Health Aspects of Alpine Hiking

A frequently asked question concerns the possible side effects of cable car journeys in individuals with pre-existing cardiovascular disease, starting from normoxia and ending at altitudes up to 3500 m. There is a lack of studies with adequate sample sizes to clarify this issue; however, moderate increases in blood pressure and heart rate, as well as a transient tendency towards supraventricular and ventricular extrasystoles, are possible.

As a stay in the Alps is usually associated with physical activity, considerations regarding a potentially positive combination of moderate hypoxia with the health effects of physical exercise were already being discussed several decades ago. However, scientific studies on the health effects of a hiking holiday only followed years after the implementation of tourism marketing strategies ("Alpine air is healthy").

In the 1980s, it was considered to offer alpine holiday dialysis specifically for patients requiring dialysis. The research findings on the effects of altitude exposure in patients with renal insufficiency were quite remarkable, especially since this patient group already exhibits reduced maximal exercise capacity at low altitude. Ergometry in dialysis patients after 3 h of exposure at 2000 and 3000 m demonstrated that, in contrast to unchanged exercise capacity at 2000 m, maximal performance at 3000 m was significantly reduced compared to low altitude (Mairbäurl et al. 1989). A 2-week hiking holiday in a hotel equipped for holiday dialysis (2000 m) was very well tolerated by the patients and even led to improved maximal exercise performance on ergometry. Thus, scientific evidence was provided that patients requiring dialysis not only do not experience adverse health effects in moderate hypoxia but may even benefit from a multi-week alpine hiking holiday (Mairbäurl et al. 1989).

Since 1998, the large-scale health tourism project AMAS (Austrian Moderate Altitude Studies) has been underway. The aim of AMAS I was to analyse the effects of a 3-week hiking holiday on individuals with metabolic syndrome, with the primary focus in the initial study on medical safety. The background was that, at the time, many textbooks generally advised against stays at moderate altitude for patients with hypertension. However, this contradicted tourism observations that it was precisely people with metabolic syndrome who chose to holiday in the Alps, as they subjectively benefited greatly from mountain holidays. The first AMAS project demonstrated that a 3-week, active, and individually tailored hiking holiday at moderate altitude was very well tolerated by all individuals with metabolic syndrome and led to significant cardiovascular (including reduction of hypertension) and metabolic improvements (Schobersberger et al. 2003).

These changes occurred independently of dietary behaviour, as there were no dietary restrictions. Thus, the safety aspect for holidaymakers with metabolic syndrome was clearly demonstrated. In the follow-up AMAS I study, the study design was maintained, and the altitude group was compared with a low-altitude group.

The results of the 2003 pilot study were confirmed (Greie et al. 2006): no "side effects" during the stay in moderate hypoxia, reduction in blood pressure over a 24-h observation period, improvement in metabolic profile (including improvement in HOMA index, reduction in fat mass, reduction in LDL cholesterol). Additional benefits were identified through analyses of psychological tests and various well-being questionnaires (Strauss-Blasche et al. 2004). Similar results were also observed in the low-altitude group; however, there were altitude-specific improvements in oxygen transport in the altitude group due to the rightward shift of the oxygen dissociation curve (Schobersberger et al. 2005). Echocardiographic measurements in moderate hypoxia revealed no differences between moderate or low altitude (Mair et al. 2008).

AMAS II investigated the effects of a 1-week active holiday (1700 m) in individuals with high stress levels. In addition to haematological changes (increase in circulating endothelial progenitor cells), the mountain holiday led to a significant reduction in stress, as verified by biopsychological parameters and HRV (heart rate variability) measurements (Theiss et al. 2008; Schobersberger et al. 2009). Similar results, with improvements in various quality-of-life parameters, were found in working individuals after a 7-day alpine hiking holiday (Huber et al. 2022). It has recently been demonstrated that the positive psychological effects of an alpine hiking holiday depend on the extent of physical activity and the duration of the holiday (Schlemmer et al. 2019).

In alpine health tourism, the focus is not only on demonstrable objective improvements in medical parameters, but also on the subjective assessment of the health interventions by the holidaymakers. It has been shown that future physical activity increases when exercise interventions have a positive effect on subjective assessment in terms of the so-called affective well-being (Rhodes and Kates 2015). In comparison to an inactive control situation, and also compared to an indoor exercise session, a randomised crossover study found that a 3-h mountain hike led to significant improvements in affective well-being (including activation and lack of energy) (Niedermeier et al. 2017). Mountain hiking thus represents an excellent intervention for positively influencing affective well-being, with the environment during mountain hiking apparently providing additional benefits.

Older, healthy individuals generally tolerate a 1-week, intensive hiking program in the mountains very well. However, the cardiopulmonary and metabolic demands of mountain hiking at altitude are greater than with similar exertion at lower elevations, and physical recovery appears to take longer in moderate hypoxia (Burtscher et al. 2001). This should be considered when planning multi-day tours.

Mountain hiking/mountaineering is typically characterised by alternating uphill (concentric) and downhill (eccentric) loading of the lower limb muscles. It has long been known that physical training improves insulin sensitivity and glucose tolerance in individuals with type 2 diabetes. However, the effects on muscular glucose metabolism appear to depend on the extent of concentric and eccentric movement patterns. There is evidence that, in terms of muscle energy expenditure, downhill walking may improve glucose tolerance more than comparable uphill walking (Zeppetzauer et al. 2013).

Alpine health tourism can also be associated with negative consequences. Falls resulting in serious injury or fatality are unfortunately not uncommon during mountain hiking. The extent to which falls in alpine terrain are the result of a cardiovascular event is currently unclear. In a publication (Faulhaber et al. 2017) analysing mountain hiking accidents in Austria between 2006 and 2014, the authors showed that the number of non-fatal mountain hiking accidents increased steadily each year. Approximately, 75% of fall accidents occurred during descent, and over 80% took place on marked routes or small paths and in good weather conditions. Nearly, 44% of fatal accidents were classified as polytrauma, with a fatality rate of 6%. The proportion of male casualties was 72%. Descending from the mountain is clearly a key risk factor for falls. Critical self-assessment personal abilities, as well as appropriate route selection and planning, should be prioritised in the future to reduce the incidence of accidents.

Whereas in the past 20 years, alpine health tourism has focused mainly on investigating the effects of moderate hypoxia on the cardiovascular and pulmonary systems, there are now very recent studies on the health benefits of mountain hiking in individuals with orthopaedic problems. For example, a randomised controlled study in individuals following knee replacement surgery (total endoprosthesis, TEP) demonstrated that a 3-month hiking program in alpine regions is safe with regard to TEP loading, and that after a total of 25 hiking days and almost 10,000 m of elevation gain, no problems with the knee prosthesis occurred (Hepperger et al. 2017). In addition, the authors found improvements in subjective quality of life in the hiking group, as well as improvements in the knee injury and osteoarthritis outcome score (KOOS) and functional parameters (stair climb test, KSS).

An alpine hiking holiday undertaken by individuals with metabolic syndrome with individually tailored holiday planning and appropriate implementation is not only well tolerated but can also lead to significant improvements in all core areas such as obesity, hypertension, insulin resistance, and hyperlipidaemia.

12.4 Possible Impacts of Climate Change on Alpine Health Tourism

Regardless of the extent to which climatic change will affect the Alpine region in the future, climate change can no longer be denied. It affects alpine flora and fauna, and of course, alpine health tourism. For example, in the Alpine region, the temperature increased by about 2 °C during the 20th century (Auer et al. 2007), and further warming is predicted for the coming decades. In addition, a marked increase in summer heatwaves is forecast, which will lead to a significant rise in cardiovascular morbidity and mortality, especially in large cities (Hutter et al. 2007).

Irrespective of the fact that climate change to this extent is already negatively affecting snow conditions in the Alps, and that low-lying ski resorts are already having to contend with this, there are also potential health tourism benefits for the Alpine region. Even if temperatures rise at higher altitudes, the temperature difference compared to valley locations will persist with global warming. While sporting activities during the day become, or already are, almost impossible in lowland tourist destinations during extreme summer temperatures, physical activities at higher altitudes such as mountain hiking remain tolerable (◘ Fig. 12.1).

Climate change will also affect future ground cover with potentially allergy-inducing plants such as ragweed. In the coming decades, a dramatic increase in land area covered by allergenic plants is predicted in Europe due to global warming. Independently, the prevalence of allergic-atopic diseases continues to rise steadily. However, positive effects on patients with various allergic-atopic conditions have been described for decades due to the specific climate at moderate altitude ("altitude climate therapy"). Differences in the climate at altitude compared to valley locations and their effects on patients with allergic-atopic diseases include:

- Reduced partial pressure of oxygen and lower annual average temperatures: decreased survival of house dust mites
- Reduction in air humidity by about one third at 1500 m: decreased mould infestation
- Reduction of various airborne environmental pollutants
- Lower air density: reduced bronchial airway resistance
- Generally lower allergen content: improved lung function in allergic asthma

◘ **Fig. 12.1** Ski tour to the Wilde Hinterbergl, Stubai Alps, Tyrol. (Image rights: B. Schobersberger)

- Higher UV exposure: benefits for certain dermatological conditions (e.g. atopic dermatitis)

In a meta-analysis of 21 studies (Vinnikov et al. 2016), it was demonstrated that stays at altitude in patients with allergic asthma led to improvements in various pulmonary function parameters and inflammatory markers in almost all studies. In addition, a positive effect of hiking on patients' body awareness and self-confidence was observed. These improvements were in some cases still detectable for many weeks to months after returning to lower altitudes. Despite this robust data, many questions remain unanswered (Tong et al. 2022). It is therefore necessary in future to develop and implement clearly defined health tourism products specifically for this tourist clientele. The essential prerequisite for this is close cooperation between medicine and research on the one hand, and the tourism industry on the other. This topic is the focus of the "European Alpine Altitude Climate Treatment (AACT)" association (Fieten et al. 2021).

Based on current data, there is a high probability that asthmatics and individuals with allergic-atopic diseases will benefit from a health tourism stay at moderate altitudes in terms of improved lung function.

Conclusion

Alpine destinations are visited by several million people each year for recreation and physical activity. From a physiological perspective, the so-called moderate altitudes (up to 3000 m) offer health seekers the advantage that acclimatisation to altitude is possible in only moderate hypoxia and can be fully achieved within a few days. Individuals with pre-existing cardiovascular diseases should observe key considerations when embarking on a holiday at altitude to reduce the risk of potential cardiovascular events. These include regular training at home, minimising stress during travel, and gradual adaptation to altitude and ambient temperature with a moderate start to physical activity. An alpine hiking holiday is well tolerated by individuals with metabolic syndrome when the trip is individually planned and appropriately executed, leading to a wide range of health improvements across all core aspects of the condition. Due to the specific climatic conditions of moderate altitudes, individuals with asthma benefit from health tourism stays, experiencing improvements in lung function.

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Role and Competencies of the Expedition Doctor in Extreme Altitude Environments

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In 2023, over 450 summit permits were issued for Mount Everest (Pokharel 2023). Adding 1 to 2 Sherpas per summit aspirant, it can be estimated that around 1200 people set out towards the death zone. These figures give an impression of the challenges and demands that await expedition doctors.

13.1 History of Mountaineering at Extreme Altitudes Outside the Alps

During the twentieth century, climbing the world's highest mountains became a major challenge. Initially driven by nationalist interests, the course of the twentieth century saw a race to the highest summits on our planet.

At that time, expedition doctors were often experienced mountaineers themselves and full members of the team, who, in addition to providing medical care for the expedition, also collected valuable research data. With the end of the era of classic first ascents, the advent of commercial expeditions marked a shift from self-reliant elite mountaineers to often less experienced summit aspirants seeking to realise their summit ambitions with the help of professional high-altitude guides. Increasingly, however, these ventures took place without an expedition doctor.

The following section will outline the importance of medical support and highlight the specific requirements of an expedition doctor. As an introduction, the various types of high-altitude trekking and mountaineering will be described.

13.1.1 Trekking in Remote High Mountain Regions and Ascent of Non-technical Peaks in the 6000 m Range

More than half of all high-altitude trekking tourists organise and undertake their tours independently, much as in the Alps. Local porters or guides with varying degrees of quality offer their services to high-altitude tourists. Social media and outdoor journals create the impression that, with the right equipment and sufficient "willpower", even the most remote and inaccessible regions are open to everyone. Numerous routes are now equipped with infrastructure that is adapted to Western expectations. With careful route selection, it is therefore possible to undertake trekking tours at altitude, similar to hut-to-hut tours in the Alps. However, most of these tourists are unfamiliar with the demands of such undertakings, particularly the challenges of acclimatisation and the often lower or absent standards of drinking water and food hygiene. Altitude-specific challenges such as reduced performance, and also altitude-related illnesses, often affect this type of traveller unexpectedly.

Commercial, organised high-altitude trekking is offered worldwide by professional agencies, enabling many to fulfil their dream of mountaineering in high mountain regions. Support from porters, pack animals, kitchen staff, and reliable, knowledgeable local guides in addition to the official mountain guide provides much that is required. However, increasing competition has led to intense price wars between providers. As a result, a few days can be cut from the itinerary so that the schedule for necessary acclimatisation becomes too tight.

Uncritical delegation of responsibility to trekking organisations or agencies increases the likelihood that a planned tour will fail. Providers should be chosen carefully and not solely based on cheapness. Individual consideration of, for example, the acclimatisation strategy is essential. Even the best equipment is of no use if it cannot be utilised. Training, practice, and preparation should, of course, be an integral part of travel planning.

13.1.2 High-Altitude Mountaineering with Summit Objectives at Great and Extreme Altitudes

13.1.2.1 Classic Large-Scale Expeditions

The organisation and tactics of classic large-scale expeditions led, in the early years of expedition mountaineering, to the successful first ascents of the 14 eight-thousanders. At the time, this was considered virtually the only way to "conquer" the highest summits. Characteristic features of these large-scale expeditions included many porters and non-climbing support staff. For example, more than 500 local porters were involved in the first ascent of K2 (Desio 1955). From the mid-1970s onwards, there was a growing trend towards smaller, often more agile and faster teams. Nowadays, expeditions in the style of the national large-scale expeditions of earlier times are extremely rare. Instead, the current approach is to attempt to climb high mountains as quickly as possible, in line with the motto "fast and light". Pre-acclimatisation at home in normobaric hypoxia, helicopter transport, and similar measures are features of modern high-altitude mountaineering. The ethics of this type of high-altitude mountaineering are open to debate, but by reducing risk, the chances of a successful ascent are increased. For example, pre-acclimatised climbers on Mount Everest no longer need to climb through the notorious Khumbu Icefall multiple times, thus reducing the risk of icefall or crevasse accidents.

13.1.2.2 Private Expeditions in Small Groups

Smaller expeditions involve a small group of mountaineers, supported by only a few local porters, establishing a base camp and then making summit attempts independently from there. In most cases, the porters do not remain at base camp but return to collect the climbers after an agreed period. The climbers themselves set up the high camps, and sometimes a cook with one or two porters remains at base camp.

13.1.2.3 Commercial Expeditions Without Summit Guidance

There are now many commercial opportunities to challenge from six-thousanders up to the summit of Mount Everest. In 2023, for example, 47 expeditions were present at base camp on Mount Everest. In total, 478 summit permits were issued (Pokharel 2023), in addition to 1 to 2 Sherpas per climber. Due to the high demand, there can be competition for the limited high camp spaces, as well as rivalries or bottlenecks on the fixed routes. Thefts of oxygen, equipment, and food occur in the high camps repeatedly because of intense price competition.

A widespread organisational model is for an experienced expedition mountaineer or mountain guide to provide all logistics, but without offering summit guidance with any guarantee of safety or success. The expedition leader acts only in an advisory or coordinating capacity.

The usually highly ambitious and particularly financially well-resourced clients are—at least in theory—responsible for their own ascent from base camp, although prepared high camps, fixed ropes, oxygen, food, communications, etc. are provided by the organiser. In terms of effort and personnel resources, such expeditions resemble the classic large-scale expeditions.

According to estimates, in 2023, around 250 non-Nepalese climbers and about 300 Sherpas from support teams were successful on Mount Everest. Two climbers reached the summit without bottled oxygen (Arnette 2023a).

13.1.2.4 Commercial Expeditions with Summit Guidance

Increasing time pressure, poorer training, and a heightened need for safety have led many clients to book an ascent of an eight-thousander only with professional guidance and a guaranteed summit attempt. Summit bonuses are often agreed with the Sherpas, which in turn increases the willingness of guides to take risks. In this model, climbers are accompanied by a Sherpa who assists and, if necessary—for example, on Mount Everest—carries additional oxygen. Often, the participants themselves are not experienced mountaineers and rely on a guarantee of success that, objectively, cannot be provided. The challenging high-mountain environment is often underestimated due to the apparent safety suggested by the presence of a mountain guide. Therefore, “tragedies” are unfortunately common, even among experienced mountain guides who risk their own lives to safeguard those of their clients. In 2023, 17 people lost their lives on Mount Everest (Arnette 2023b; Service 2023).

13.1.2.5 Expedition Style and Alpine Style

Various ascent strategies, each with different requirements for logistics, planning, and execution, have become established in high-altitude mountaineering. In the so-called expedition style, a group of mountaineers, supported by a larger team of porters, high-altitude porters, cooks, and possibly guides, attempts to summit a peak. The base camp is set up first, followed by so-called rotations. During these, the climbers acclimatise on the mountain by, for example, moving from the base camp to the high camp and back again. The high camps are usually set up in advance by high-altitude porters. The ascent often follows established routes and previously fixed ropes. Once the first rotation is complete, the climbers ascend to the first high camp, spend the night there, and then move on to the next pre-established high camp, spending another night in the first camp to further acclimatise. In this way, the mountain is gradually climbed until a summit attempt is made from the final high camp. After reaching the summit, the climbers descend as far as possible, potentially all the way back to base camp.

In contrast, the alpine style involves climbing with significantly fewer porters and less logistical support but requires much more extensive planning. The climbers, possibly with the help of porters, set up a base camp and begin their ascent from there. The climbers carry their own tents, stoves, equipment, and food. A route is chosen from the base camp, and the climbers ascend to a previously selected or considered campsite. The camp is set up independently and dismantled the next day. This process continues from Camp 1 onwards until the final high camp. For the summit attempt, any unnecessary equipment is left behind, and the camp is dismantled on the way back from the summit. During the descent, the climbers again try to descend as far as possible.

In alpine-style ascents, fixed ropes are generally not used. More difficult sections are therefore protected using traditional climbing techniques, and, where possible and necessary, climbers alternate leads.

13.2 Health Risks in High-altitude Mountaineering Outside of the European Alps

As the previously mentioned figures clearly show, tourism in high-mountain regions is booming as never before. A dramatic increase in serious and fatal incidents in high-altitude mountaineering affects not only paying clients but also local porters and guides. Unfortunately, this is often not generally recognised. Ever-new records and statistics create the impression that high-altitude mountaineering is becoming "safer" and less risky, and ultimately possible for everyone.

In order to provide a realistic risk assessment of such specific undertakings and to offer appropriate information, the potential risks must first be systematically presented and made clear to both the physician and the participant.

13.2.1 Risks due to Physical Factors

- Altitude-related oxygen deficiency (hypobaric hypoxia) with altitude illnesses and reduced performance or depletion of energy reserves (hypoglycaemia)
- Cold and wind chill, with the risk of local frostbite (see ▶ Chap. 30) and general hypothermia (accidental hypothermia; see ▶ Chap. 29)
- Heat exhaustion, dehydration (hypohydration), and heatstroke
- Intense solar radiation, with risks such as snow blindness (keratoconjunctivitis) and sunburn (see ▶ Chap. 44)

The four "hypos" are a threat in high-altitude mountaineering: hypoxia, hypothermia, hypohydration, and hypoglycaemia.

13.2.2 Risks due to Biological Factors

- Bacterial, viral, or parasitic infections of the gastrointestinal tract, respiratory tract, and skin (see ▶ Chap. 43)
- Poor water quality and perishable food supplies
- Toxic plants, allergic reactions, arthropod bites with disease transmission, and bites from venomous animals such as spiders, scorpions, and snakes
- Endemic tropical diseases such as malaria, schistosomiasis, yellow fever, leishmaniasis, sleeping sickness, and many others

13.2.3 Hazards due to Environmental Dangers

- Burial by avalanche, icefall, rockfall, crevasse fall, and falls from height
- Flooding and mudslides
- Snowstorm, lightning strike, and sandstorm
- Volcanic activity and earthquakes
- Wild animal attacks
- Traffic accidents and plane crashes

13.2.4 Hazards due to Personal Problems

- Anxiety, isolation, and homesickness (see ▶ Chap. 46)
- Exacerbation of pre-existing medical conditions (see ▶ Chap. 21)
- Inadequate preparation and briefing

13.2.5 Hazards due to Political Influences

- Kidnapping
- Civil unrest and physical assaults
- Terrorist attacks and acts of war

13.3 Consequences for Responsible Decision-Makers

A physician participating in an expedition or journey initially provides a sense of security for the other members. As a result, it is common to find offers from expedition organisers who grant discounts to doctors in exchange for the expectation that the doctor will assume responsibility for the medical care of the participants. This creates the impression of a safety net for participants, which, given the potential hazards in the mountains, does not actually exist. It is essential to issue a clear warning before accepting such offers. The effort required to provide medical support for an expedition should not be underestimated. It is important to be fully aware of one's own value as well as the medical and personal challenges involved.

13.3.1 Medical Responsibilities and Requirements

Expedition doctors face a broad and complex set of requirements. Once the decision is made to accompany an expedition in a medical capacity, participants are entitled, for both legal and ethical reasons, to expect care from a qualified physician trained in mountain, altitude, and expedition medicine. The International Society for Mountain Medicine (ISMM), in cooperation with the Medical Commission of the Union Internationale des Associations d'Alpinisme (UIAA) and the Medical Commission for Alpine Rescue (ICAR), has established the minimum standard for this by developing the International Diploma in Mountain Medicine (DiMM).

National professional societies, such as the Austrian Society for Mountain and High Altitude Medicine (ÖGAHM) and the German Society for Mountain and Expedition Medicine (BexMed), have adopted the training and examination requirements necessary to obtain the DiMM. Through these societies, it is possible to first acquire the Diploma in Mountain Medicine and subsequently the Diploma in Wilderness and Expedition Medicine.

Despite the availability of this high-quality training, many organisers still prefer, for cost reasons, to operate without a qualified expedition doctor. This position is now untenable, both legally and ethically.

From a legal perspective, particularly in Austria, liability must be examined in detail, as without completion of general medical and/or specialist training, there is no full professional authorisation for independent medical practice in the sense of a right to practice.

13.3.2 Implications for the Organiser

Unfortunately, many long-distance travellers assume that worldwide travel health insurance, a satellite phone or GPS emergency transponder, and pre-arranged coverage for rescue costs provide a sense of perceived security.

The reality in many remote areas is far more sobering. There is often a lack of established, organised rescue infrastructure. Helicopter flights are only possible with advance payment guarantees and usually only after significant delays. In many cases, these helicopters are not equipped for casualty transport, and there is often no designated receiving hospital for such flights. Furthermore, in many regions, a possibly corrupt and at times overburdened bureaucracy further complicates matters, thereby hindering search and rescue operations.

An effective health safety net exists nowhere in the world outside Europe and parts of North America. Therefore, the *necessity of qualified medical supervision for trekking and high-altitude expeditions is unquestionable.*

For the safety of the participants, there is a moral dimension, and for the safety of the organiser, a legal one. If an expedition needs to be aborted or altered due to medical necessity, neither the organiser nor the expedition doctor should be held responsible or liable for any affect on the trip's success. Furthermore, the subsequent reimbursement of costs for transport and medical treatment depends on a qualified medical assessment.

13.3.3 Significance for Privately Organised Trips

Due to ongoing development of remote areas, easier access to information, and the influence of social media, regions that were once isolated are now attracting increasing numbers of tourists and adventure seekers. Increasingly, individuals without sufficient experience find themselves in environments and situations for which they are inadequately prepared.

It is often apparent that travellers are neither familiar with the criteria for successful acclimatisation to high altitudes nor willing to adapt to the necessary requirements regarding time and route planning. In many cases, inexperienced individuals transfer their responsibility and decision-making authority entirely to local tour operators. A typical example of such an undertaking is the ascent of Kilimanjaro. Precise data collection is difficult, but it is estimated that around 50% of Kilimanjaro aspirants develop altitude sickness (Jackson et al. 2010).

If, even before departure, the decision is made to forgo a doctor for cost reasons, at the very least, a consultation with a qualified physician should be sought well in advance of the trip. Training, instruction, pre-travel examinations, and provision of the necessary prescription medications are then core responsibilities of the consulting trekking and expedition doctor, who should also be available for any necessary follow-up care after the expedition.

13.4 Professional Profile of the Trekking and Expedition Doctor

The field of expedition medicine is a specialised area that requires particular medical skills. The limited or absent overarching healthcare infrastructure presents a major challenge. The combination of required competencies is not found in any other medical specialty. Key areas of expertise include general medicine, internal medicine, emergency medicine, and sports medicine, as well as trauma and visceral surgery. Basic knowledge of tropical and travel medicine is also beneficial. In addition, a crucial area of expertise is the specialised field of high-altitude medicine.

The working environment of the expedition doctor is often hostile, at times dangerous, and frequently markedly different from clinical standards in Europe. Quick thinking and a willingness to improvise are essential. The professional profile can be divided into three qualification criteria, which are often required simultaneously: clinical skills, mountaineering competence, and personal suitability. It must be ensured from the outset that all aspects of this requirement profile are met.

13.4.1 Clinical Skills of the Expedition Doctor

The expedition doctor acquires clinical skills during specialist training or through relevant additional qualifications. Diplomas in mountain and expedition medicine, which focus intensively on high-altitude medicine, have already been mentioned. Further training in acute and emergency medicine is beneficial, both because it broadens professional competence and because pre-hospital medical practice often requires and develops a higher degree of improvisation. Basic surgical skills, such as wound management, should be known and mastered. In particular, the expedition doctor must be able to deal with challenging hygiene conditions and, if necessary, initiate and monitor appropriate countermeasures.

Below are some common tasks presented as examples; this list is intended as a planning aid.

13.4.1.1 Before the Expedition

- Completion of a medical questionnaire with evaluation, particularly regarding pre-existing conditions, allergies, etc.
- If necessary, conducting or reviewing a current assessment of physical performance.
- Travel medicine advice, and review and updating of vaccination status.
- Obtaining detailed information about the approach route and planned ascent with particular focus on ascent and altitude profile, medical and rescue infrastructure, and, if applicable, the current tropical medicine situation, including antibiotic use, local resistance patterns, and prophylactic measures.
- Risk assessment and development of an emergency plan including communication, transport, and medical treatment options.
- Training of participants in first aid and preparation of medical equipment.
- Prior to the expedition, participants should also be provided with knowledge regarding the symptoms and risks of altitude sickness.

13.4.1.2 During the Expedition

- Monitoring of tropical medicine protocols, water disinfection, food hygiene, personal hygiene, and radiation protection
- From the threshold altitude above 2500 m, monitoring of acclimatisation for all participants, including support staff such as cooks and porters
- Medical care of participants, noting that fixed treatment times have proven effective
- Checking the medical equipment and handing it over to specifically designated porters

13.4.1.3 At Base Camp

- Setting up a medical station in a designated tent, consisting of a couch (e.g. made from cargo containers), the base camp pharmacy, an oxygen therapy unit, diagnostic instruments, and surgical equipment. Here the doctor primarily attends to the injured, the ill, and those seeking advice.
- Instructing participants in the use of medical equipment, such as hyperbaric bag therapy.
- Explanation of the use of high-altitude medical kits and emergency oxygen. In general, medical interventions should only be carried out on the doctor's orders, either in person or via radio. Oxygen must always be carried up with the first load of camp equipment.
- Intensive training of participants in the symptoms and treatment of altitude sickness.
- Monitoring the health status, performance, and acclimatisation of all participants, with timely advice or treatment as needed.
- Checking personal first aid kits.

13.4.1.4 During the Establishment of High Camps

- The expedition doctor should also participate in the necessary acclimatisation process.
- While the doctor is at the high camps, a designated and trained assistant is responsible for the base camp medical station and radio communications.
- The doctor always carries the emergency kit in their rucksack, ensuring emergency care is available during all phases of the ascent.

13.4.1.5 General Principles

- All relevant events should be documented in detail in a logbook.
- Personal summit ambitions may only be pursued following a decision by all responsible parties, considering the current medical support situation, and should be discussed before the expedition. In case of doubt, summit ambitions should be reduced.
- As most emergencies occur on the mountain, permanent presence in base camp is not a realistic scenario. “The doctor comes to the patient” remains a fundamental principle in high-altitude mountaineering.
- In individual cases, the expedition doctor must leave base camp either to attend to patients further up the mountain or to accompany transport down to the valley.
- As in pre-hospital emergency medicine, the basic principle applies that self-protection takes precedence over the protection of others.
- It may occur that the doctor is also involved in the treatment and care of the local population. Whether the role is to be extended in this way should be considered before the expedition, and the expedition pharmacy adjusted accordingly.

13.4.1.6 After the Expedition

- Preparation of a report based on the logbook
- Care and counselling of ill participants and referral to specialists
- Coordination and implementation of necessary follow-up examinations and discussion of findings

13.4.2 Mountaineering and Expedition Skills

The expedition doctor operates in an environment where they must act as an independent and self-reliant mountaineer in challenging terrain, including rock and ice climbing, and under extreme weather conditions. This requires a high level of skill and physical fitness. The doctor must not only ensure their own safety but also have significant responsibility for the expedition members entrusted to their care. This role demands:

- At least several years of basic training and experience in summer and winter mountaineering
- Sound practical knowledge of mountain rescue techniques, including patient evacuation safety requirements, anchor construction, abseiling techniques, and bivouac construction
- Organisational and operational skills: selection and establishment of a safe campsite, kitchen, and toilet area, and supervision of drinking water and food hygiene
- Proficient use of modern navigation (GPS) and communication technology

13.4.3 Requirements for Personal Skills

In order to make rapid and goal-oriented decisions in emergency situations, it is necessary to have not only individual characteristics but also clearly defined rules and unambiguous decision-making authority.

13.4.3.1 Authority and Decision-Making Competence

Task allocation, responsibilities, and command hierarchies within the team should be discussed in advance.

- Who is the ultimate decision-maker?
- What influence does the doctor have on the course of the expedition?
- How, for example, are individual differences in acclimatisation times addressed?
- Who mediates disagreements between the expedition leader and the doctor?

13.4.3.2 Self-Confidence and Empathy

An expedition represents an exceptional situation for both participants and the doctor. The accompanying doctor may encounter a range of expectations, fears, concerns, and psychological challenges, which may also affect them personally. Fundamental principles of medical practice can serve as a guiding framework.

- Recognising one's own strengths, weaknesses, and limitations
- Assisting everyone, regardless of prejudice or emotion
- Sensitive handling of participants' fears of loss and failure
- Ability to improvise and manage conflicts

13.4.3.3 Managing Participants' Expectations

- Discussing participants' expectations and clarifying the limitations of actual assistance options.
- Emphasising and reinforcing the high degree of personal responsibility and instructing the team in risk reduction.
- Providing care for the entire team, including support staff, according to uniform medical standards.
- Minor illnesses are the individual's responsibility but should nevertheless be taken seriously.

13.4.3.4 Ethical and Moral Conflicts with Expedition Objectives

- Respect for each participant's autonomy and their right to make decisions about themselves, to accept advice, or to refuse treatment. This requires clear patient information and communication skills.
- If the patient's judgement is impaired, for example, in the early stages of high-altitude cerebral oedema, the doctor must assume responsibility for decision-making, following the principle of preventing harm to the patient.
- Encouraging compassion and mutual support, even in seemingly hopeless situations. This requires prior training and scenario simulation.
- It is advisable to discuss expectations and objectives upon arrival at base camp at the very latest, including the possibility of failure or accidents.
- Ensure fairness, equality, and justice within the group.
- Show respect for the culture, traditions, and regulations of the host country.

Are the expedition members a close-knit team that succeeds together but is also prepared to turn back together if necessary? Or is it an interest group of individual mountaineers who may continue the summit attempt alone? These and similar questions must be clarified before the expedition.

13.5 Dealing with Known Pre-existing Conditions and Limitations

In an increasingly ageing society, there are a growing number of trekking participants with complex pre-existing conditions who have nevertheless successfully completed demanding tours.

Most published recommendations for managing pre-existing conditions are based on theoretical considerations, are rarely supported by practical evidence, and primarily address altitude-related respiratory and cardiovascular problems. The lack of studies and limited experience often result in a cautious or conservative approach when advising. However, with appropriate planning, precautionary measures, and supervision, mountaineers with a range of pre-existing conditions can also successfully undertake challenging mountain tours. Due to the complexity of this topic, a separate chapter is dedicated to it (see ▶ Chap. 21).

The expedition doctor must address participants' pre-existing conditions in a timely and comprehensive manner. Even complex pre-existing conditions do not necessarily constitute grounds for exclusion.

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Medical Equipment for High-Altitude Trekking and Expedition Mountaineering

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The selection of medical equipment will always be a compromise, determined by the specific nature of each expedition. Medical teams must recognise that due to remoteness and weight/volume constraints, comprehensive preparation for all medical scenarios is impossible. The most common and especially the most serious illnesses and injuries should provide a guide for the selection and scope of medical supplies.

14.1 Common or Serious Medical Conditions During High-Altitude Trekking and Expeditions

14.1.1 Common, Initially Mild but Treatable Conditions

At high altitude, wound healing is markedly impaired. Wind and dry air further impede the healing process of "simple" wounds. Additionally, infection risk increases due to compromised hygiene conditions.

Therefore, if seemingly minor injuries such as blisters, pressure ulcers, abrasions, ocular infections, or oral mucosal inflammation (including labial herpes simplex infections) occur, meticulous treatment is essential to prevent more serious health problems.

14.1.2 Environment-Related Causes of Illness

Environment-related illnesses are directly linked to the location of the expedition. For high-altitude expeditions, altitude-related conditions including acute mountain sickness (AMS), high-altitude pulmonary oedema (HAPE), high-altitude cerebral oedema (HACE), and mixed presentations should be expected. In addition, cold injuries such as hypothermia or local frostbite may occur, while heat-related illness may occur even in glaciated high-altitude environments. Dehydration, exhaustion, and radiation-induced keratitis (snow blindness) are also common.

During travel to the expedition site, preparation should be made for bites or stings from venomous animals, which may lead to allergic reactions.

Classic hazards such as snowstorms, lightning strikes, rockfall, icefall, avalanches, and crevasse falls are often present, even on expeditions to foreign countries. A comprehensive understanding of these potential risks is therefore of utmost importance to ensure the safety of the entire expedition team.

14.1.3 Common Internal Medical Conditions

The most common medical conditions include infectious diseases such as gastrointestinal illnesses, infections of the upper and lower respiratory tract, and soft tissue infections. Prompt treatment is one of the main responsibilities of the expedition physician in order to prevent progression, which may even necessitate a participant's withdrawal from the expedition.

14.1.4 Serious Internal Medical Conditions

Allergic reactions, which can be fatal if left untreated, must be promptly recognised and managed. Asthma attacks, seizures, or severe abdominal complaints must also be treated appropriately. A particular challenge is posed by non-specific chest pain. Acute psychological conditions including anxiety crises, hyperventilation, and panic attacks must also be considered in the differential diagnosis.

14.1.5 Serious Injury Patterns

These include traumatic brain and spinal injuries, blunt chest and abdominal trauma, pelvic and femoral fractures, and open fractures.

14.1.6 Tropical Diseases

These include *Plasmodium falciparum* malaria, amoebiasis with abscess formation, giardiasis, schistosomiasis, helminth infections, fungal infections, skin parasites, and arthropod bites with transmission of infection.

14.1.7 Pain, Bleeding, Respiratory Problems, and Unconsciousness

A minimum equipment supply for haemostasis, thermal protection, splinting, positioning, and improvised evacuation is just as important as equipment for appropriate pain management, ventilation, and the treatment of unconscious patients.

14.2 Organisation, Scope, and Contents

The medical equipment for an expedition can be divided into the following main categories: base camp medical kit (transported to base camp where it remains, but also available during approach and return), physician's emergency bag, and individual participant medical kits.

In principle, it has proven effective to divide the medical equipment into separate units according to their main purpose and logistical requirements. The materials are pre-sorted and stored in special boxes or containers. Storing all equipment in a single container should be avoided, as loss during approach would result in complete equipment failure, so that if there is loss, then at least part of the equipment is preserved. The expedition physician should always have access to the individual boxes, which should be organised as practically as possible according to individual needs. A logical approach would be to divide the units according to specific medical conditions such as altitude sickness, pain, gastrointestinal disorders, and respiratory infections. Some very commonly used medications, such as cough suppressants, cold remedies, and analgesics, should be available in sufficient quantities.

In addition, a "diagnostic box" has proven useful, containing a stethoscope, blood pressure cuff, thermometer, spatula, blood glucose meter, etc. Separate boxes can also be prepared for wound care, surgery, and airway management. An ampoule case should also be carried, containing the standard emergency ampoules in accordance with current emergency medicine guidelines, along with the necessary accessories.

Factors influencing the selection of medical equipment for expeditions:

- Number of participants and support staff (porters, high-altitude porters, kitchen staff, mountain guides)
- Provision of care to the local population
- Duration and nature of the approach and return journey, length of stay at base camp, total duration of the expedition
- Risk profile of the expedition, number of high camps, rescue options, evacuation logistics
- Distance to and quality of the nearest hospital, possibility of rapid repatriation

The decision regarding the scope and composition of the expedition medical equipment rests solely with the expedition physician. However, it is important that the expedition organiser is informed about the type and scope of the medical equipment, in order to organise the logistical transport of the materials and prevent damage (clearly labelled as "Medical Box").

The expedition leader is responsible for organising the necessary oxygen cylinders, including masks and regulator systems. The inspection should be carried out together and far enough in advance so that problems can be addressed.

The expedition physician should ensure that, in particular, expensive medical equipment on loan (ultrasound scanner, defibrillator, etc.) is adequately insured. In most cases, this can be arranged through the expedition organiser and should be confirmed in advance.

The import of medicines and medical devices is subject to different regulations by airlines (regarding transport) and in the various destination countries. Information is usually available from the relevant authority in the destination country or the foreign representation in the home country. A list of the medicines in English should always be carried, along with a valid medical licence and a letter of assignment from the organiser. Special regulations apply to controlled substances (opiates/benzodiazepines); information is provided by the relevant diplomatic mission of the destination country.

14.2.1 Base Camp Medical Kit

The following base camp medical kit recommendations are designed for typical commercial expeditions, consisting of participants, porters, high-altitude porters, mountain guides, and a base camp team with local staff. Generally, no further medical infrastructure is available on site.

The medical kit should (as described above) be stored in waterproof, impact-resistant boxes or cases that are clearly marked as medical equipment from the outside and equipped with a locking mechanism so that the boxes can be secured. Inside, a list of the medications, including quantities, dosages, and indications, can be attached in waterproof transparent sleeves. It has proven useful to organise the medications according to illnesses (symptoms), to ensure that participants can easily find them. In principle, medications should only be dispensed by a doctor; if no doctor is present at base camp, a designated person must be appointed to take on this responsibility.

14.2.1.1 Medication Box, Organised by Indication

- **Altitude Sickness**

Dexamethasone 4 mg tablets, nifedipine retard 20 mg tablets, acetazolamide 250 mg tablets

- **Antibiotics**

Azithromycin 500 mg tablets, amoxicillin 250 mg/clavulanic acid 125 mg tablets, ciprofloxacin 500 mg tablets, clindamycin 600 mg tablets, metronidazole 400 mg tablets, doxycycline 200 mg tablets. (Note: observe current guidelines and resistance developments!)

- **Analgesics**

Ibuprofen 400–600 mg tablets, tramadol retard 100 mg tablets, diclofenac rapid 50 mg tablets, hyoscine butylbromide tablets

- **Gastrointestinal Agents**

Proton pump inhibitors (PPI) e.g. pantoprazole 40 mg tablets, ondansetron 4 mg tablets, loperamide 2 mg tablets, probiotics, electrolyte powder, sodium picosulfate capsules/drops (for constipation)

- **Airways/Cough**

- Cough suppressants: Noscapine 2 mg tablets
- Expectorants: Ambroxol tablets
- Various throat lozenges
- Antipyretics: Paracetamol 500 mg tablets

- **Drops/Sprays**

- Eye drops: Single-dose corticosteroid eye drops, diclofenac eye drops, oxybuprocaine eye drops, single-dose antibiotic eye drops

- Nasal drops/spray
- Other: Salbutamol inhaler, nitrolingual spray

Ointments/Solutions

Topical corticosteroid ointment (hydrocortisone 1% ointment), topical antibiotic ointment (neomycin/bacitracin ointment), analgesic gel (diclofenac gel), dexpanthenol wound healing ointment, dexpanthenol eye/nasal ointment

Povidone-iodine solution, octenidine solution for wound and mucosal disinfection

Allergy

- Desloratadine 5 mg tablets
- Epinephrine (adrenaline) auto-injector

Frostbite

Acetylsalicylic acid (aspirin) 100 mg tablets, enoxaparin 4000 IU pre-filled syringes

Agitation

- Lorazepam 2 mg tablets

Other

- Aciclovir 800 mg tablets

Box: Trauma

Clothing scissors, SAM splint, cervical collar, local haemostatic dressing or haemostatic agent, self-applying pressure bandage, Israeli emergency bandage, 14 Fr indwelling urinary catheter including accessories

Box: Wound Care

Needle holder, clamp, forceps, scissors, disposable scalpels, non-absorbable suture material, wound closure strips, tissue adhesive, stapler, triangular bandage, tubular bandages, eye pads, wound dressings, rescue blanket, plasters, tape, kinesiology tape, disposable gloves

Box: Infusions

Balanced electrolyte solution 500 ml, isotonic saline solution 0.9% 250 mL and 100 mL, glucose 5% 500 mL, infusion sets including accessories

Box: Respiratory

Bag-valve-mask and filter, oro-pharyngeal airways, maybe laryngeal tubes including accessories

Box/Pack: Diagnostics

Stethoscope, blood pressure cuff, thermometer, otoscope, pulse oximeter, blood glucose meter, urine test strips, pregnancy test, pen torch, spare batteries

Box/Pack: Equipment

Ultrasound device, defibrillator

Box/Pack: Ampoule Case

The contents of the ampoule case should be assembled according to current emergency medicine guidelines and the emergency medical competence of the expedition physician. It should cover the anticipated emergency medical interventions. Only those medications that the expedition physician is actually familiar with and competent to use should be taken.

As an expedition physician, every medical intervention should be carefully considered, especially those that fall within the scope of emergency medicine. It is important to note that evacuation or transport, even from a base camp, is often very difficult, as helicopter flights are frequently not possible. The equipment carried by helicopters in most cases is limited to that of standard transport helicopters, with no medical equipment on board and no doctor present.

(Due to current developments changes are expected in the coming years; therefore, it is advisable to obtain sufficient information in advance regarding helicopter transport. Country-specific differences should be considered.)

14.2.2 Personal Equipment/Individual First Aid Kit for Participants

Each participant should carry their own individually assembled first aid kit in their daypack, independent of the group's medical equipment. This should primarily contain any personally required medications, such as diabetes medication, epinephrine (adrenaline) auto-injector for those with allergies, etc.

Include only medications and equipment that participants are familiar and competent to use. It is advisable to keep the first aid kit small, compact, and lightweight, as it will be carried.

A basic kit for a personal first aid pack may include the following:

- Hydrocolloid blister dressings, tape
- Sterile wound dressings, wound fixation material, wound disinfectant
- Analgesics: e.g. paracetamol 500 mg tablets, ibuprofen 400 mg tablets
- Lozenges
- Antihistamine: e.g. desloratadine 5 mg tablets
- Antiemetic: e.g. ondansetron 4 mg orodispersible tablets
- Antidiarrheal: e.g. loperamide 2 mg tablets
- Sunscreen SPF 50
- Emergency blanket
- Disposable gloves

14.2.3 Personal Documents

Identification documents (passport, including a copy), insurance documents (in duplicate, with one copy deposited with the travel agency), visa (including a copy), flight documents (with rebooking options), cash, credit cards, contact addresses and telephone numbers of relatives, allergy card if required (in English), list of medications for those on regular medication (in English with a doctor's prescription)

14.2.4 Physician's Emergency Bag

This kit must remain accessible to the expedition physician throughout the journey to enable an appropriate response in the event of an emergency. The contents may vary depending on the doctor's specialty and the destination and should be adapted accordingly. A minimum standard in line with emergency medicine should be maintained:

- **General Equipment and Dressing Materials**

- Stethoscope, pulse oximeter, clinical thermometer, fine-tip forceps, disposable scalpel, scissors, disposable gloves, pen torch, emergency blanket, SAM splint
- Dressing materials: Wound covering film (e.g. OPSITE Flexifix PU foil), pressure dressing for haemostasis, wound disinfectant solution, wound closure strips, sterile compresses, non-adherent wound dressings, wound bandage

- **Medications**

- Altitude sickness: Dexamethasone 4 mg tablets, nifedipine retard 20 mg tablets, acetazolamide 250 mg tablets
- Pain: Ibuprofen 600 mg tablets, paracetamol 500 mg tablets, opioid analgesic
- Frostbite: Acetylsalicylic acid (Aspirin) 100 mg tablets
- Cough suppressant: Noscapine 25 mg lozenges/tablets
- Gastrointestinal: Loperamide 2 mg tablets, ondansetron 4 mg tablets
- Other: Lorazepam 2 mg tablets, desloratadine 5 mg tablets, epinephrine(adrenaline) auto-injector
- Sprays/drops: Nitrolingual spray, salbutamol spray, oxybuprocaine eye drops, diclofenac eye drops

- **Ampoules**

The selection of ampoules should be based on the emergency medical expertise of the expedition physician and must cover the anticipated emergency medical interventions (► Sect. 14.2.1).

14.3 High-Altitude Medical Kit

The high-altitude medical kit should be considered a small emergency kit containing only the most essential medications in the simplest form, so that every participant is able to use them.

The high-altitude medication kit, including ibuprofen 600 mg tablets, is essential, accompanied by a written brief guide indicating when each medication should be taken and at what dosage.

In addition, oxybuprocaine eye drops should be included for snow blindness, as well as acetylsalicylic acid (aspirin) tablets for frostbite. Avoid respiratory depressant medications, as ventilation support during high-altitude rescue operations is extremely challenging. It is important to note that during a rescue at high altitude, it is often impossible to monitor vital parameters as thoroughly as would be done in emergency medicine at lower altitudes.

> The most essential medication that must be carried in sufficient quantity on high-altitude expeditions is oxygen (including accessories).

Standard oxygen cylinders are filled with 4 L at 300 bar. The most commonly used regulator systems can deliver a flow rate of up to 4 L/min, with some regulators allowing up to 8 L/min. The expedition physician must check and verify this in advance at base camp. It is also essential to calculate and plan where (i.e. at which altitude/camp/depot) and how many oxygen cylinders should be stored to ensure adequate supply if needed. Sufficient spare regulators and masks should also be available.

A planning or logistical error in this can be fatal!

14.4 Summary

Increasing travel to high-altitude regions outside Europe, characterised by limited rescue capabilities and healthcare infrastructure, is associated with health risks that must not be underestimated. Careful advance planning is therefore essential. The medical equipment taken depends primarily on the type and nature of the journey, the number of participants and accompanying team, and particularly the personal experience of the physician.

> Equipment should only be carried if the expedition physician is familiar with its use.

Specific considerations such as antimalarial prophylaxis depend on the planned itinerary. It is advisable for each participant to have their vaccination status checked and, if necessary, updated before departure. Vaccination certificates should be carried in both original and copy.

15

From High Altitude to Intensive Care Medicine

Marc Moritz Berger and Jürgen Knapp

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15.1 Human Hypoxia Tolerance

During the Caudwell Xtreme Everest Expedition in 2007, arterial blood samples were collected from four mountaineers at an altitude of 8400 m under ambient conditions and without supplemental oxygen. In these samples, the mean arterial PO_2 was 24.6 mmHg (range: 19.1–29.5 mmHg), and the accompanying O_2-saturation was 54% (Grocott et al. 2009). These values, among the lowest ever recorded in humans, illustrate the extent of hypoxia that needs to be tolerated during an ascent of Mount Everest without supplemental oxygen.

Numerous studies have investigated human hypoxia tolerance and the underlying adaptive and compensatory mechanisms. These studies have not only improved our understanding of high-altitude physiology and pathophysiology but have also enhanced our knowledge of the effects of hypoxia in critically ill patients. The physiological adaptation processes observed in mountaineers exposed to high-altitude hypoxia appear, at least in part, to be relevant for hypoxia tolerance in critically ill patients as well. Therefore, a better understanding of high-altitude physiological processes may also be of significance in the field of intensive care medicine (Berger and Grocott 2017). Studies involving mountaineers acutely exposed to high altitude offer the advantage over intensive care patients in that the effects of hypoxia can be investigated in a relatively homogeneous group without significant confounding factors. In contrast, a wide range of variables (e.g. comorbidities, medications) must be considered in critically ill patients. These very factors may also limit the spectrum of adaptive and compensatory mechanisms available to a healthy mountaineer.

15.2 Alveolar Fluid Reabsorption

One example of how studies in high-altitude medicine have expanded our pathophysiological understanding of other disease entities is the mechanism of alveolar fluid reabsorption. Alveolar fluid reabsorption is primarily based on transepithelial ion transport (◘ Fig. 15.1).

> In individuals susceptible to high-altitude pulmonary oedema (HAPE), transepithelial ion transport appears to be impaired, at least under hypoxic conditions (Sartori et al. 2002).

As a result, reabsorption of fluid from the alveolar space is reduced, at least in hypoxia or at altitude, thereby promoting the development of pulmonary oedema. β-sympathomimetics stimulate transepithelial ion transport, which can be exploited therapeutically. Inhalation of the β-sympathomimetic salmeterol, for example, can reduce the risk of developing HAPE at 4559 m in susceptible individuals by approximately 50% (Sartori et al. 2002). The concept of stimulating alveolar fluid reabsorption with β-sympathomimetics has subsequently been applied to patients with severe respiratory failure (acute respiratory distress syndrome, ARDS). In these patients, the capacity for alveolar fluid reabsorption is also significantly reduced and is associated with increased mortality (Matthay 2002). An initial pilot study in 40 patients showed promising results, as intravenous salbutamol, compared to placebo, led to a reduction in extravascular lung water and duration of mechanical ventilation (Perkins et al. 2006). However, a subsequent multicentre study in 324 ARDS patients was terminated early because intravenous

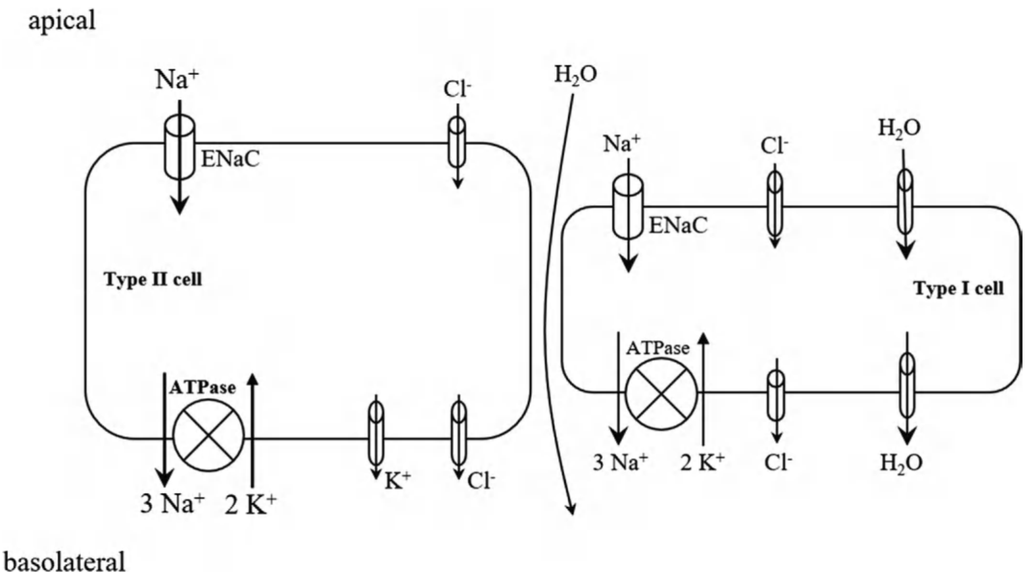

Fig. 15.1 Schematic representation of transalveolar ion and water (H_2O) reabsorption. The reabsorption of oedema fluid depends on transepithelial sodium (Na^+) transport, which generates an ion gradient that passively drives the movement of oedema fluid. Na^+ enters the cell via apical epithelial Na^+ channels (*ENaC*). On the basolateral side, Na^+ exits the cell into the interstitium via the Na^+/K^+ adenosine triphosphatase (*ATPase*). In exchange, K^+ transported into the cell by the Na^+/K^+-ATPase leaves the cell along the outwardly directed K^+ gradient. Na^+ reabsorption is accompanied by chloride (Cl^-) reabsorption. The resulting Na^+ and Cl^- gradients provide the driving force for transepithelial, paracellular fluid reabsorption

administration of salbutamol was poorly tolerated due to tachycardia and arrhythmias and was associated with increased 28-day mortality (Gao Smith et al. 2012). Despite this disappointing result, the mechanism of alveolar fluid reabsorption remains an interesting target for future strategies in the treatment of pulmonary oedema. A promising approach is the relatively new agent solnatide (laboratory code AP301), which, when administered as a liquid aerosol, activates pulmonary ENaC. Whether solnatide leads to a clinically relevant improvement in outcomes in patients with pulmonary oedema is currently under investigation (Schmid et al. 2022).

15.3 Hypoxic Pulmonary Vasoconstriction

An optimal ventilation-perfusion ratio in the lung is crucial for maintaining adequate tissue oxygenation, especially under hypoxic conditions. Hypoxic pulmonary vasoconstriction (HPV) leads to redistribution of blood flow from hypoxic regions to better-oxygenated areas of the lung (Sylvester 2001). This mechanism is particularly advantageous in cases of localised alveolar hypoxia or hypoventilation. At altitude, however, HPV is not physiologically beneficial, as hypoxia is present throughout the lung rather than being locally restricted, resulting in a generalised increase in pulmonary vascular pressures.

> Haemodynamic measurements using pulmonary artery catheters in individuals susceptible to HAPE at 4559 m have shown that the main factor in the pathophysiology of HAPE is an increased, inhomogeneous HPV.

This inhomogeneous HPV leads to increased pulmonary capillary pressures in areas of high perfusion or in regions with pulmonary venous vasoconstriction, thereby promoting the leakage of fluid into the lung interstitium and alveoli (and thus the development of HAPE) (Fig. 15.2). However, in HAPE, there is no impairment of left ventricular function or increase in left atrial pressure (Maggiorini et al. 2001). A hypoxia-induced imbalance between vasodilators (including nitric oxide) and vasoconstrictors (including endothelin-1), as well as increased production of reactive oxygen species, appears to be central to the exaggerated HPV observed in individuals susceptible to HAPE (Bailey et al. 2010; Berger et al. 2005, 2009). Such alterations are found not only in HAPE, but also in other forms of pulmonary hypertension and in ARDS (Albertine et al. 1999; Klinger et al. 2013; Lau et al. 2017). This demonstrates that findings from studies in healthy individuals exposed to acute hypoxia are also relevant to other forms of pulmonary hypertension and ARDS.

15.4 Capillary Density

At high altitude, there is an increase in cardiac output (primarily due to an increase in heart rate), ventilation, and, over time, haemoglobin concentration (see ▶ Chap. 6). These adaptive mechanisms ensure that oxygen transport to the periphery remains adequate. However, sufficient capillarisation is a prerequisite for adequate tissue oxygenation.

> In tissues with high oxygen dependence, such as skeletal muscle, reduced oxygen availability leads to an increase in capillary density.

In mountaineers exposed to high altitude (5250 m), increased capillary density can be demonstrated in muscle groups of both the legs and arms (Hoppeler and Vogt 2001; Mizuno et al. 2008). If increased capillarisa-

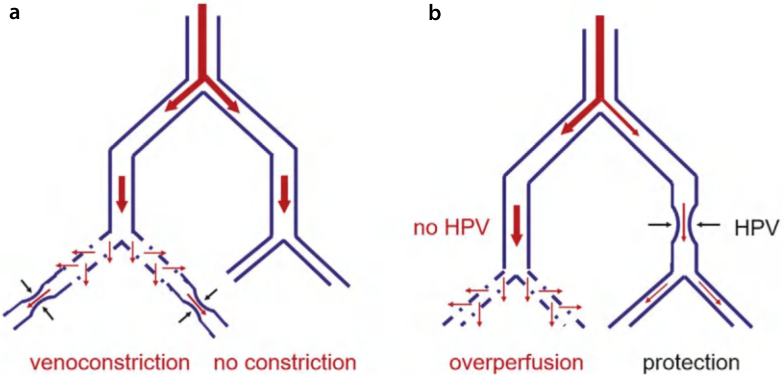

Fig. 15.2 Schematic representation of the mechanisms by which hypoxic pulmonary vasoconstriction (*HPV*) may lead to increased pulmonary capillary pressures and leakage of fluid into the lung interstitium and alveoli. **a** The principle of postcapillary venoconstriction (Zhao et al. 1993). **b** The principle of inhomogeneous precapillary vasoconstriction (Hultgren 1996)

tion does not occur under hypoxic conditions, peripheral oxygen delivery is impaired. During an ascent of a 7126 m peak (Mount Himlung Himal, Nepal), higher capillary density was associated with a greater likelihood of reaching the summit.

In patients with severe sepsis who develop tissue hypoxia as part of shock, higher capillary density is associated with lower mortality (Hoppeler and Vogt 2001; Mizuno et al. 2008). A key mechanism for increasing capillary density is the hypoxia-inducible factor 1 (HIF-1) (Pugh and Ratcliffe 2003; Semenza 2012), whose discovery was awarded the Nobel Prize in Physiology or Medicine in 2019. In various forms of shock, HIF-1 concentrations are elevated (Textoris et al. 2012). However, whether these increases are relevant for survival remains unclear. Therapeutic administration of HIF-1 during hypoxia in shock is under discussion as a means to increase the capillary density of vital organs in critically ill patients (Pugh and Ratcliffe 2003; Villani et al. 1998).

15.5 Mitochondrial Metabolic Processes

During acclimatisation to high altitude, not only is oxygen transport increased, but there is also a reduction in oxygen utilisation (Kayser 1996). Explanations for this may be found at the subcellular level in the mitochondria. Their density in skeletal muscle decreases following acclimatisation to high altitude and, at the same time, the capacity for oxidative phosphorylation to generate adenosine triphosphate (ATP) is also reduced. A shift in energy production from primarily glucose utilisation towards increased fatty acid oxidation in the mitochondria confers energetic advantages. In addition, for the same amount of oxygen consumption, more ATP is produced according to the caloric equivalent (Murray and Horscroft 2016). A direct consequence of these adaptive processes is a reduction in oxygen demand. The actual oxygen requirement for maintaining ATP production in the mitochondria is tissue-dependent and lies at a PO_2 of approximately 1–5 mmHg (Gnaiger et al. 1995). It is known from hypoxia-tolerant animal species that adaptation to hypoxia does not occur via activation of anaerobic metabolic pathways, but rather through a reduction in aerobic oxygen consumption by limiting cellular processes (e.g. ion transport, protein synthesis) (Hochachka et al. 1996).

In septic patients, similar adaptive responses appear to be of significance: In most cases, the initial phase of sepsis is characterised by a hyperdynamic circulatory state with increased cardiac output, whereas in the later course of the disease, as cardiac output normalises, the reduction of mitochondrial metabolic processes, particularly oxidative phosphorylation, becomes predominant (Singer 2014). In this phase, increasing oxygen delivery appears to be detrimental (Helmerhorst et al. 2015).

> The response to acute hypoxia in both critically ill and healthy individuals during acute hypoxic or high-altitude exposure initially consists of upregulation of oxygen transport mechanisms, whereas, over time, a reduction in oxygen consumption becomes the predominant response.

15.6 Genetic Factors

The considerable individual variability in altitude tolerance and physical performance at altitude is poorly understood. It is also unclear why some critically ill patients can tolerate arterial PO_2 values <60 mmHg for days without significant organ dysfunction, while others cannot (Helmerhorst et al. 2015). The cause of these phenotypic differences in hypoxia tolerance may be genetic in nature. It is conceivable that genetic variants leading to improved altitude tolerance are also associated with increased survival in hypoxia-related diseases (Berger and Grocott 2017). However, robust data supporting these hypotheses are scarce. For example, a deletion-insertion polymorphism has been described in the gene encoding angiotensin-converting enzyme (ACE), which is associated both with improved altitude tolerance (Wang et al. 2016) and with reduced mortality in the presence of ARDS (Marshall et al. 2002). Upregulation of the so-called heat shock protein 70 during sepsis is also associated with increased hypoxia tolerance and a reduced risk of developing ARDS (Aschkenasy et al. 2011).

Conclusion

Studies of healthy individuals at high altitude have made a significant contribution to a more comprehensive understanding of the physiological and pathophysiological effects of hypoxia on the human organism. Since hypoxaemia is also frequently observed in critically ill patients (either as a cause or consequence of various disease states), insights gained at high altitude can help to better understand the effects of hypoxaemia in intensive care patients and to develop new therapeutic strategies. In particular, the mechanisms leading to a reduction in cellular oxygen consumption are likely to be of therapeutic interest in the future.

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Alpine Sports Medicine

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Specific Muscular Load Patterns in Alpine Sports

Marc Philippe

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The load patterns encountered in alpine environments are primarily defined by the topography of the terrain and the sports practised there. The topography of alpine landscapes has always fascinated people, but in earlier times, it was also associated with hard and sometimes dangerous work. The use of alpine areas for sport is closely linked to human curiosity and the desire to explore new parts of the world. The "pointless" ascent of mountains, especially summits, significantly predates the concept of "sport". The first ascent of Mont Ventoux (1902 m) by Francesco Petrarch on 26 April 1336 is considered to be the birth of mountaineering.

The basis of almost all alpine sports is the steep gradient of the alpine regions. In addition to mountaineering, a wide variety of sports are practised in these areas. Sports can be categorised into those performed on land, on water, or in the air. The most common land-based sports are hiking, mountaineering, trekking, running (mountain and trail running), climbing (sport, alpine, technical, and ice climbing), mountain biking, e-mountain biking, road cycling, skiing (Alpine and Nordic), cross-country skiing, tobogganing, snowshoeing, and ski touring. On water, rafting, canoeing, and canyoning (partly on land) are popular, and winter sports also take place on water. Air activities include paragliding and hang gliding (delta gliding).

16.1 Popular Mountain Sports

The most popular summer sports in the Alps are hiking, mountaineering, mountain biking, and climbing, with hiking being the most popular. According to the World Tourism Organization (WTO/IOC 2001), in 1999, over 4.7 million German holidaymakers cited summer mountain sports and almost 4.2 million winter mountain sports as their main reason for travel.

Skiing and snowboarding are the most popular winter sports, with skiing being the leading winter sport in the Alps. Austria alone records approximately 50 million skier days annually (WKO 2024). All these mountain sports are also practised away from the Alps. Trekking and mountaineering expeditions are becoming increasingly popular, especially in the world's major mountain ranges.

■ What Sport- and Environment-Related Stresses Must Alpine Athletes Expect?

All alpine sports (except indoor climbing) are outdoor activities, and thus the varied natural environment is ever-present. In high mountain regions, rapidly changing weather conditions can turn seemingly easy tours into challenging or even extreme situations within a very short time. In such cases, psychological resilience and specific coping strategies are required to manage the situation. The more extreme the terrain, the more alpine athletes need, in addition to physical and mental fitness, experience, planning, and knowledge of hazards. A central factor that increases the difficulty of exercising in high mountains is the decrease in atmospheric pressure with altitude and the associated hypoxia. ► Chaps. 19 and 20 examine this topic in greater detail.

The most popular alpine sports share the characteristic that, in addition to the usual physical abilities such as endurance, strength, and strength endurance, specific coordination aspects play a major role. Compared to walking on level ground, mountain hiking requires greater surefootedness and improved balance. Mountain biking also demands a high degree of skill and, depending on the terrain, an advanced riding technique. Climbing has a specific set of requirements. In addition to physical characteristics (see below), climbing requires good technique and sound knowledge of belaying methods. Skiing and snowboarding also place particularly high demands on coordination and require specific techniques that must be learned.

Hiking and mountaineering, skiing and snowboarding, but also, albeit to a lesser extent, mountain biking share a characteristic specific to mountain sports: in flat-terrain sports (e.g. hiking or road cycling), the main form of load on the major muscle groups in the legs is concentric, whereas in mountain sports, there is a significant eccentric component in addition to the concentric load.

16.2 Eccentric and Concentric Loading

Eccentric loading, which is a distinctive feature of alpine sports, also occurs in many other sports but rarely to the same extent as in mountaineering/hiking or skiing/snowboarding. This can be illustrated using the example of hiking and mountaineering. The primary load on the leg muscles involved is almost exclusively concentric when ascending and almost exclusively eccentric when descending. When going uphill, the muscles overcome gravity by the fibres contracting/shortening (= concentric). When going downhill, the muscles are used to counteract gravity by lengthening in a controlled manner (= eccentric).

On long mountain tours, during trekking and high-altitude mountaineering, heavy equipment is usually carried, which further increases both concentric and eccentric loading. Eccentric loading also plays a significant role in mountain biking. Challenging descents are usually tackled in a standing position. Even though modern suspension systems absorb much of the eccentric work, the leg and arm muscles must still absorb and cushion many impacts eccentrically. Eccentric muscle loading is also important in both skiing and snowboarding. In both sports, the legs function like a spring: they must absorb shocks in a controlled manner (eccentric) and actively rebound (concentric). The differences between concentric and eccentric muscle loading are explained in more detail in the following sections.

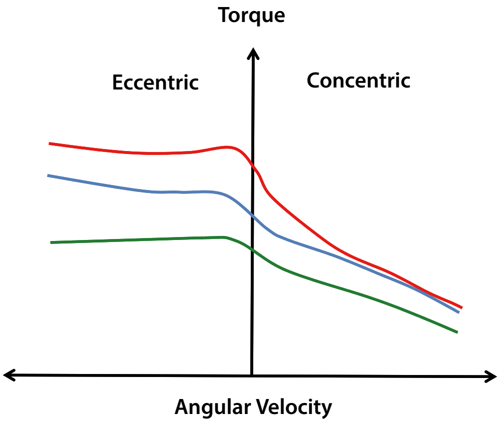
16.2.1 Eccentric vs. Concentric Torque

The torque generated by a muscle depends on the contraction speed. The faster the muscle contracts (concentric), the less force it can generate. During maximal isometric contraction (muscle contraction without shortening or lengthening of the muscle fibres), the muscle can generate the greatest voluntary force. In vitro experiments have shown that a muscle stretched (eccentric) under maximal tension can produce greater forces than during maximal isometric contraction. The force also increases with increasing stretch velocity (Edman et al. 1978; Katz 1939).

In vivo measurements have not demonstrated that maximal eccentric loading results in significantly higher torque than maximal isometric loading (Babault et al. 2001; Webber and Kriellaars 1997; Westing et al. 1988; ◘ Fig. 16.1). This appears to be primarily due to an intrinsic muscle protection mechanism that limits the recruitment of motor units during eccentric loading (Webber and Kriellaars 1997).

16.2.2 Load-Specific Fibre-Type Activation

Many studies have investigated whether concentric and eccentric loading results in characteristic patterns of muscular innervation (Enoka 1996; Komi et al. 1987; Bigland and Lippold 1954). Early studies found that during eccentric muscle contractions, fewer motor units are activated than during concentric contractions (Komi et al. 1987; Bigland and Lippold 1954). This is remarkable, as maximal eccentric contractions pro-



◘ **Fig. 16.1** Relationship between torque and angular velocity in the knee joint at three different angles (30° = *green* line; 40° = *blue* line; 60° = *red* line). (Mod. after Westing et al. 1988)

duce higher forces at all stretch velocities than maximal concentric contractions at any shortening velocity (◘ Fig. 16.1).

One possible explanation for this phenomenon is that during eccentric contractions, fast-twitch (FT) motor units, which can generate greater forces than slow-twitch (ST) motor units, are recruited before the slow-twitch motor units. This would result in a reversal of the classical “size principle” of recruitment during eccentric contractions (small motor units predominantly contain ST fibres, whereas large motor units increasingly contain FT fibres) (Nardone and Schieppati 1988; Nardone et al. 1989).

A study by McHugh et al. (2002) supports this hypothesis. They found that even at intensities of 25% of maximal voluntary contraction (MVC) during eccentric loading, significantly higher frequencies in the electromyography (EMG) signal were observed (indicating activation of fast-twitch motor units) compared to the same concentric loading of the quadriceps. This significant difference persisted at 50% and 75% of the MVC. At 100% MVC, there were no differences in the EMG signal frequency. This could be explained by the fact that during concentric loading, the EMG signal frequency increased steadily with intensity, whereas during eccentric loading, the EMG signal frequency remained constant as the load increased.

Other research groups have not reached this conclusion and have assumed that the “size principle” of recruitment is maintained even during eccentric contractions (Stotz and Bawa 2001; Komi et al. 2000). Research groups employing molecular biological methods have also concluded that the recruitment hierarchy is preserved during eccentric contraction (Beltman et al. 2004a). Reviews by Chalmers (2008) and Duchateau and Baudry (2014) indicate that there is still no clear consensus regarding recruitment strategies during eccentric contractions. However, the prevailing view is that the classical recruitment principle is generally maintained.

> ❯ The specific innervation pattern during eccentric contraction is not yet fully understood.

16.2.3 Kinematic, Kinetic, and Neural Control Strategies

Several studies have investigated the specific loading patterns (kinematic, kinetic, and neural) of uphill and downhill walking (Franz and Kram 2012, 2013; Franz et al. 2012; Lay et al. 2006, 2007). All studies found that uphill, downhill, and level walking are governed by different control strategies.

Franz et al. (2012) found that step frequency and double support time (the period during which both feet are in contact with the ground) did not differ between uphill and level walking, but both step frequency and double support time decreased significantly during downhill walking from a gradient of −3° onwards (gradients studied: −9° to +9°). The positive work performed by one leg during a complete step increased by 276% at a +9° incline compared with level walking. The negative work performed by one leg during a complete step increased by 283% at a −9° decline compared with that during level walking.

Lay et al. (2006) found that the kinematic changes during uphill and downhill walking, compared with level walking, are related to the situational need for toe clearance or heel strike and the elevation or controlled lowering of the body's centre of mass. Overall, both uphill and downhill walking resulted in a significant increase in the lower limb supporting moment compared with level walking. In uphill walking, this increase was primarily attributed to a significant increase in the hip extensor moment. During downhill walking, there was a significant increase particularly in the knee extensor moment.

Consistent with this finding, Lay et al. (2007) and Franz and Kram (2012) reported that the muscle activity of the knee extensors, as measured by EMG, increased significantly during downhill walking compared with level walking. In contrast, during uphill walking, there was a significant increase in the muscle activity of the hip, knee, and ankle extensors compared with level walking.

Furthermore, Franz and Kram (2013) found that with increasing age, there is a disproportionate increase in the activation of the hip extensor muscles (particularly the gluteus maximus) during uphill walking, whereas the co-activation of the antagonists does not differ from that of younger individuals. However, the authors were unable to determine the precise cause of this observation.

Uphill and downhill walking are subject to specific control mechanisms that may change over the course of life.

16.2.4 Energy Expenditure During Uphill and Downhill Walking

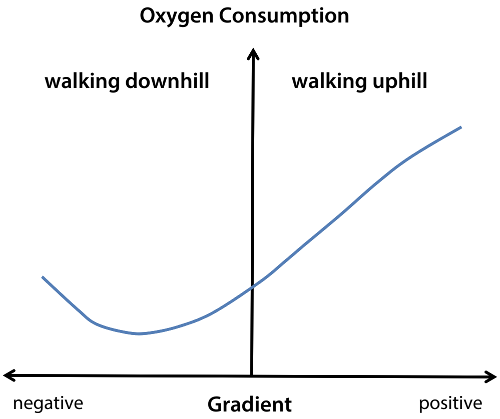
Data on energy expenditure during uphill and downhill walking and running do not present a consistent picture (Franz et al. 2012; Beltman et al. 2004b; Johnson et al. 2002; Minetti et al. 2002; Laursen et al. 2000). This is due, among other factors, to the highly variable measurement methods and protocols used in individual studies. The most common method for measuring energy expenditure is the assessment of oxygen uptake and carbon dioxide output (spirometry).

In addition to this method, energy expenditure can be measured using mechanical work or molecular biological techniques. In particular, calculating energy expenditure based on mechanical work performed can lead to misestimations during eccentric loading because, as already mentioned in ► Sect. 16.2.2, even at high eccentric loads, the muscle requires less neural activation than during equivalent concentric loads. In addition to a different recruitment strategy, it is assumed that eccentric loading leads to mechanical stretching of the cross-bridges between actin and myosin, which can be broken without the use of adenosine triphosphate (ATP) (Flitney and Hirst 1978). In in vitro experiments with maximally stimulated muscle fibres, eccentric loading also resulted in a 70% lower energy expenditure compared to concentric loading (Beltman et al. 2004b).

Franz et al. (2012) calculated, using 12 young adult participants, that during a complete step on level ground, the positive mechanical work of one leg was 0.29 ± 0.03 J/kg/step. In contrast, during a complete step at a slope of +9° (equivalent to +15.7%), it was 1.09 ± 0.10 J/kg/step. For a complete step on level ground, negative work of −0.26 ± 0.03 J/kg/step was calculated. This increased to −0.99 ± 0.07 J/kg/step at a slope of −9°. The walking speed under all three conditions was 1.25 m/s.

Comparing these findings with the results of Minetti et al. (2002) makes it clear that calculating eccentric energy expenditure solely based on mechanical work would lead to an overestimation. They measured an energy expenditure of 1.64 ± 0.50 J/kg/m during level walking. At a gradient of +10%, the energy expenditure was 4.68 ± 0.34 J/kg/m and increased almost linearly to 17.33 ± 1.11 J/kg/m at a gradient of +45%. At a gradient of −10%, the energy expenditure dropped to 0.81 ± 0.37 J/kg/m before rising again to 3.46 ± 0.95 J/kg/m at −45%. Energy expenditure values were calculated using oxygen consumption and carbon dioxide output, as well as the respective caloric equivalents.

These results are consistent with those of Johnson et al. (2002). They also observed a decrease in oxygen uptake during downhill walking at a slight negative gradient and a slight increase in oxygen uptake at steeper negative gradients (◘ Fig. 16.2). At the same walking speed, they reported a 50% reduction in oxygen uptake during downhill walking compared to uphill walking. This results in a two-fold higher oxygen consumption for uphill walking at the same speed. This indicates that walking downhill is twice as efficient as walking uphill. The heart rate is also correspondingly lower during downhill walking, analogous to oxygen uptake.



◘ **Fig. 16.2** Oxygen consumption during uphill and downhill walking at a walking speed of 1.1 m/s. (Mod. after Johnson et al. 2002)

Snow further impedes this progress. At a sinking depth of 45 cm, a fivefold increase in energy expenditure was measured compared to that at a sinking depth of 0 cm (Pandolf et al. 1976). The authors also reported that sustained trail breaking in snow at 50% of maximal oxygen uptake is possible at a sinking depth of 20 cm with a maximum speed of 0.67 m/s and at a sinking depth of 10 cm with a maximum speed of 1.12 m/s without snowshoes (Pandolf et al. 1976).

The use of poles leads to a partial redistribution of load from the lower to upper extremities (Bohne and Abendroth-Smith 2007; Schwameder et al. 1999). This is particularly advantageous when additional weights (e.g. rucksacks) need to be carried. The literature does not provide a clear consensus on how walking with poles affects the energy expenditure. While some authors found no difference in energy expenditure during uphill and downhill walking with or without poles (Foissac et al. 2008; Jacobson et al. 2000), others observed increased energy expenditure when walking with poles on level ground and at various negative and positive gradients (Saunders et al. 2008). Downhill walking with poles may be responsible for the overall increase in energy expenditure when walking with poles (Perrey and Fabre 2008).

> The energy expenditure during uphill walking is approximately twice as high as that during downhill walking (at the same speed).

16.2.5 Eccentric Loading and Muscle Damage

Eccentric loading is less demanding on the cardiovascular system than concentric loading but leads to higher mechanical stress on the muscles, resulting in a different pattern of neural activation. In particular, in individuals who are not yet accustomed to eccentric loading, this can result in muscle damage, which manifests as muscle pain (Fridén and Lieber 2001; Rodenburg et al. 1993). Well-trained individuals are less affected by the negative effects of eccentric loading (Skurvydas et al. 2011), whereas in less well-trained individuals, eccentric loading can lead to muscle pain and temporary reductions in strength, sprint performance, and endurance capacity (Byrne and Eston 2002; Gleeson et al. 1998). In addition, muscle damage can affect energy supply.

Studies using ^{31}P-magnetic resonance spectroscopy (^{31}P-MRS) have shown that eccentric loading can lead to changes in muscle metabolism (Davies et al. 2011; Newcomer et al. 2005; Lund et al. 1998; Rodenburg et al. 1994). Walsh et al. (2001) found no change in muscle oxygenation (measured by near-infrared spectroscopy [NIRS]) after eccentric loading. In contrast, Ahmadi et al. (2008) observed impaired muscle oxygenation persisting up to 4 days following intense eccentric loading, whereas Walsh et al. (2001) found no notable alterations in any markers of muscle damage.

As previously mentioned, trekking poles can help redistribute some of the load from the lower to the upper extremities. When used correctly (appropriate length, parallel pole placement, etc.) during downhill walking, trekking poles can help protect the joint structures of the lower extremities and reduce muscle damage and thus muscle pain (Bohne and Abendroth-Smith 2007; Howatson et al. 2011; Schwameder et al. 1999). This is particularly true for individuals who are overweight or carrying heavy rucksacks (Cho and Roh 2016; Bohne and Abendroth-Smith 2007).

> Eccentric loading is largely responsible for the development of delayed-onset muscle pain.

16.2.6 Adaptations to Eccentric Loading

Although acute eccentric loading can have negative effects on muscle function and metabolism, it also protects against further damage from subsequent eccentric loads performed in close succession (Maeo et al. 2015; Green et al. 2010). The predominantly positive effects of chronic eccentric loading, particularly in the context of strength training, have been well documented. Regular eccentric loading leads to beneficial adaptations in strength and kinematics (Elmer et al. 2011). In recent years, it has become increasingly clear that eccentric loading can directly induce both peripheral and central nervous adaptations associated with neuromuscular control. Accordingly, eccentric training modalities can be effectively used after injuries, such as anterior cruciate ligament rupture, to specifically address muscular imbalances. Moreover, eccentric loading is gaining importance in injury prevention and fall prophylaxis (Lepley et al. 2017).

Positive immunological and metabolic adaptations can also be induced by eccentric loading (Philippe et al. 2017, 2019; Drexel et al. 2008, 2021; Paschalis et al. 2010). Since eccentric loading results in high mechanical but low cardiovascular strain, this form of exercise can also benefit individuals with cardiovascular and pulmonary diseases, for example, during the initial phase of rehabilitation (Camillo et al. 2020; Gremeaux et al. 2010; Steiner et al. 2004).

16.2.7 Practical Relevance

The previous sections have shown that alpine sports such as mountaineering, hiking, and skiing present specific and unfamiliar types of physical stress for untrained individuals. Current mountain hiking accident statistics indicate that approximately 75% of all hiking accidents occur during the descent (Faulhaber et al. 2017, 2020). As eccentric loading can acutely lead to muscle pain and fatigue and negatively affect strength and endurance performance, it is important to consider this, especially for untrained individuals, at the start of the season, and in general mountain sports and tour planning.

However, the potentially positive effects of eccentric loading should not be ignored. Many ski resorts operate (limited) cable car services even in summer. People whose cardiovascular or pulmonary capacity is insufficient for prolonged uphill walking can take the cable car up and walk down (provided there are no orthopaedic problems, the routes are chosen appropriately, and, if necessary, trekking poles are used). This could provide optimal muscle training with minimal cardiovascular strain and serve as preparation for future tours involving gentle ascents.

16.3 Loading Patterns in the Special Case of Climbing

There are various disciplines of climbing. The following sections, however, refer only to the currently most popular form: free climbing or sport climbing.

16.3.1 Oxygen Uptake and Energy Supply

For the past 20 years, research has increasingly focused on the physiological factors that determine climbing performance. The determination of energy requirements and the type of energy supply in sport climbing is fundamental to all further research.

Many research groups have compared oxygen uptake during climbing with that measured during maximal cycle or treadmill ergometer tests (Sheel et al. 2003; Booth et al. 1999; Watts and Drobish 1998; Mermier et al. 1997; Watts et al. 1996; Billat et al. 1995). All authors observed comparatively low oxygen uptake during climbing relative to VO_2 peak on the treadmill or cycle ergometer. The results of the previously mentioned studies indicate that only 37.7–51.2% of the VO_2 peak achieved on the treadmill or cycle ergometer is utilised during climbing, suggesting that aerobic capacity is not a limiting factor.

In contrast, all of the above-mentioned authors reported a disproportionately high increase in heart rate during climbing. Furthermore, even at submaximal workloads, lactate values were recorded, which indicated possible exertion above the individual anaerobic lactate threshold. Assuming that the anaerobic threshold in healthy individuals lies between 60% and 90% of VO_2 max (see ► Chap. 19), the blood lactate values at the observed oxygen uptake levels should be significantly lower. Together with the disproportionately high heart rate values, this suggests that both systemic aerobic and local anaerobic metabolic processes are relevant during climbing. Bertuzzi et al. (2007) estimated the anaerobic lactic contribution to energy production at 22.3% of the total energy expenditure.

Aerobic capacity is not a performance-limiting factor in climbers.

16.3.2 Performance-Limiting Factors in Climbing

Noé et al. (2001) demonstrated that the load on the upper extremities, and particularly on the fingers, increases with the steepness of the climbing angle. When these findings are combined with those of Watts and Drobish (1998), who found that there was no significant increase in oxygen uptake with increasing angle (overhang) on the same route, it becomes clear and understandable that the lactate produced during climbing is generated predominantly in the upper extremities, especially in the gripping muscles.

Therefore, the high demand placed on the upper extremities is the origin of the disproportionately high increase in heart rate compared to oxygen uptake, as the smaller muscle groups of the upper extremities elicit a greater sympathetic drive than the activation of the large muscle groups of the lower extremities when stressed (Zouhal et al. 2008; Davis et al. 1974).

> Metabolic acidosis in the forearm muscles is considered the main cause of fatigue during climbing (Giles et al. 2006; Schöffl et al. 2006; Sheel 2004).

16.3.3 Strength and Endurance Capacity of the Finger Flexor Muscles in Climbers

► Section 16.3.2 suggests that climbing performance depends to a large extent on the capacity of the finger flexor muscles. Climbing thus occupies a special position, as there are few sports in which such small muscle groups are crucial for performance. This has led researchers to focus intensively on the strength and endurance capability of the gripping muscles.

A handgrip dynamometer is typically used to measure the maximal voluntary grip or pinch strength. As a handgrip dynamometer is not very climbing specific, many research groups have developed climbing-specific finger flexor strength tests (Schöffl et al. 2006; Wall et al. 2004; Grant et al. 1996).

In addition to the use of different measuring devices, the selection of test and control groups makes it extremely difficult to compare individual study results. Overall, these studies indicate that elite climbers possess higher relative and absolute maximal finger strength than non-climbers. However, these results are always highly dependent on the expertise of the climbers and the characteristics of the control group (Philippe et al. 2012; MacLeod et al. 2007; Vigouroux and Quaine 2006; Wall et al. 2004; Grant et al. 1996, 2001, 2003; Ferguson and Brown 1997).

In addition to the maximal strength of the finger flexor muscles, muscular endurance is of utmost importance in climbing. Endurance performance on a climbing ergometer has been identified as a predictive factor of climbing performance (España-Romero et al. 2009). In the literature, both isometric continuous and intermittent finger flexor endurance tests have been described. The latter is more representative of the demands of climbing.

White and Olsen (2010) reported that professional male climbers in bouldering competitions exhibited a work-to-rest ratio of 13:1. The ratio of rest duration between attempts to the duration of exertion during attempts was estimated to be 4:1. The demands of bouldering are not directly comparable to those of lead climbing. Nevertheless, a ratio of 13:1 clearly demonstrates that climbing is characterised by a constant alternation between relatively long periods of exertion and short recovery phases. Schädle-Schardt (1998) reports a typical work-to-rest ratio of 10:3 for sport climbing.

Several research groups have demonstrated that both female and male climbers, especially those participating in competitive climbing, were able to perform significantly more repetitions in an intermittent finger flexor endurance test at 40–80% of maximal strength (Philippe et al. 2012; Vigouroux and Quaine 2006; Ferguson and Brown 1997).

Ferguson and Brown (1997) attributed the superior performance of climbers in climbing-specific endurance tests to greater forearm muscle perfusion compared to non-climbers, as measured by plethysmography. MacLeod et al. (2007) and Philippe et al. (2012) found, using near-infrared spectroscopy (NIRS), that climbers exhibited a greater increase in oxygen saturation in the finger flexor muscles during the 3-s rest intervals between exertions than non-climbers. Occlusion experiments also revealed faster reoxygenation of the finger flexor muscles with increasing climbing ability. This may indicate an improved oxidative capacity of the finger flexor muscles (Fryer et al. 2016).

> The strength and endurance capacity of the hand and forearm muscles are of paramount importance for climbing (Saul et al. 2019).

Conclusion

A distinctive feature of many mountain sports in terms of muscular loading patterns is the disproportionately high proportion of eccentric movements. Eccentric muscle loading differs from concentric loading in terms of its demands and adaptation mechanisms. Eccentric loading is characterised, among other things, by the generation of very high muscular peak loads with simultaneously low metabolic expenditure. In individuals who are not adapted to eccentric loading, this often leads to muscle pain, and accidents during mountain hiking occur predominantly during the descent. Adaptation to such loading results in specific morphological and neurophysiological muscle adaptations, which can have positive effects on strength, movement kinematics, metabolism, and the immune system.

Sport climbing is characterised by the importance of small muscle groups. The strength and endurance capacity of the hand and forearm muscles are overriding performance-determining factors.

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Training Theory and Ascent Strategy in Mountain Hiking and Mountaineering

Martin Faulhaber and Hannes Gatterer

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Well-developed endurance and strength capacities are fundamental for safe and successful mountaineering. In line with the motto “no pain, no gain”, appropriate training should be done regularly. A sound ascent strategy is a prerequisite for optimal application of these abilities during a tour.

17.1 General Principles of Training Design

There are many principles for initiating, regulating, and consolidating training adaptations, a selection of which are described here.

17.1.1 Regularity

Training sessions should be performed regularly, i.e. without extended breaks. This is because during periods of reduced training or even training abstinence, cardiorespiratory, metabolic, and neuromuscular adaptations are lost. The rate of decline varies and depends on fitness level, training history, type of training, and genetic factors (Garber et al. 2001).

17.1.2 Effective Training Stimulus and Progression

A load below a certain threshold is ineffective for improving performance (Garber et al. 2001). This threshold is individual and depends on performance level. For example, moderately trained individuals require an intensity of 70–80% of maximal oxygen uptake (VO_2 max), whereas highly trained endurance athletes need to train close to their maximum (95–100% of VO_2 max) to improve VO_2 max (Midgley et al. 2006).

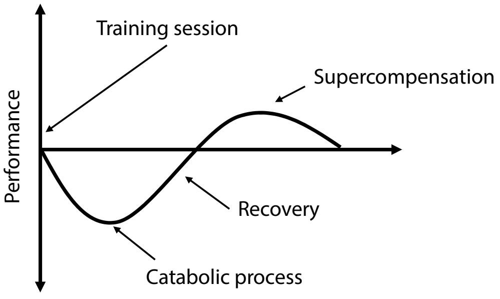
In untrained individuals, however, an intensity of approximately 40% of VO_2 max is sufficient to achieve a training effect (Swain and Franklin 2002). Consequently, training stimuli must be progressively increased as performance improves in order to achieve long-term training success. A constant training stimulus (e.g. running the same distance at the same speed) quickly loses its performance-enhancing effect (Zintl and Eisenhut 2009).

17.1.3 Alternation of Load and Recovery

The stimuli set by training (e.g. glycogen depletion as a catabolic process) induce a specific adaptation (e.g. anabolic response) during the recovery phase. The concept of supercompensation (◘ Fig. 17.1) assumes that this compensation exceeds the initial level and subsequently leads to improved performance (Astrand et al. 2003). If recovery periods are too short or too long, training adaptations are impaired. Ideally, a new training stimulus should be applied at the point of maximal supercompensation. However, supercompensation is not applicable to all adaptations and is controversial (Tschien 2006).

17.1.4 Individualisation

The extent of training adaptations, the ability to recover from intense training loads, as well as the time available and



◘ **Fig. 17.1** Supercompensation

individual training preferences, all vary greatly both between and within individuals. For example, some people respond rapidly and with marked hypertrophy to strength training, while others show significantly less adaptations. Similarly, the amount of time available for training per week can quickly change, for instance due to changes in work commitments. Optimal training should take these circumstances and changes into account and adjust the training time, content, and intensity of training accordingly.

17.1.5 Periodisation and Specification

Long-term training should be structured specifically to the training goal, such as a planned trekking tour, and divided into different phases (training periods). While highly differentiated periodisation models exist for elite sport, a simplified model with three periods and the following key features is presented here for practical use in mountain sports.

General preparation:
- Broad and non-specific training content
- Low to moderate intensities
- Progression through continuous increase in training volume

Specific preparation:
- Training targeted to the demands of the planned activity (e.g. long tours with a heavy rucksack)
- Training in the expected environmental conditions (e.g. cold) and with the appropriate equipment
- Reduction of training load approximately 1 week before the start of the activity to ensure optimal recovery (in mountaineering projects, this often coincides with organisational preparation and a multi-day journey)

Transition period:
- Focus on targeted physical and psychological recovery
- Change of activity (e.g. swimming or cycling) and marked reduction in training time and intensity

17.2 Training of Motor Skills Relevant to Mountain Sports

The demands of mountain sports activities, both physical and coordination ability, are highly complex (see ► Chap. 16). Endurance, in the form of general aerobic endurance, is a key physical capacity in almost all mountain sports disciplines. In addition, specific strength abilities are important not only in climbing, but also in mountaineering (e.g. core strength when carrying a heavy rucksack). Therefore, the following sections focus specifically on training for aerobic endurance and strength abilities (see ► Sects. 17.2.1 and 17.2.2).

Coordination abilities important for mountain sports, such as balance, can often be trained together with endurance or strength. Long-term training should be goal-oriented and follow the training principles outlined above.

The following points should generally be observed:
- Medical examination before starting training for new and returning participants over 55 years (women) or 45 years (men), for individuals with known pre-existing conditions, or with symptoms such as dizziness or shortness of breath during low-intensity activity (based on American College of Sports Medicine 2022).
- Adaptation phase during the first 4 weeks with very low training intensities to ensure adequate acclimatisation to exercise load and to consolidate technically correct movement execution.

- No training in the presence of signs of infection (e.g. fever, muscle aches, sore throat, unusual fatigue).
- Warm-up phase (10–15 min) at low intensity at the beginning of each session (e.g. light jogging or aerobic exercise to music).
- Cool-down phase at the end of each session (e.g. jogging with relaxation exercises).
- The effectiveness of stretching at the beginning or end of training for injury prevention or improved recovery remains controversial and certainly depends on individual implementation (Rubini et al. 2007; Woods et al. 2007; Herbert et al. 2001).

17.2.1 Endurance Training

17.2.1.1 Intensity Regulation in Endurance Training

The heart rate reserve method (HRR) according to Karvonen is one way to regulate training intensity. HRR is calculated by subtracting the resting heart rate (HRrest) from the maximum heart rate (HRmax). To determine the heart rate range for the targeted training intensity (e.g. 60% or 80% of HRR), the percentage of HRR is added to the resting heart rate.

▶ Example

Training heart rate (132 bpm) = ([HRmax (180 bpm) − HRrest (60 bpm)] × % intensity [0.60]) + HRrest (60 bpm) (American College of Sports Medicine 2022).

HRmax can be determined by a maximal exercise test in the laboratory or alternatively by a maximal 400-m run in the field (but only for acclimatised healthy exercise-accustomed individuals). To estimate HRmax, the formula HRmax = 220—age can also be used, although this has an error range of up to 15 bpm and thus can represent considerable inaccuracy for intensity prescription (Wonisch et al. 2003; Whaley et al. 1992). HRrest is determined by repeated morning measurements (lying in bed before getting up).

Another method for regulating training is the assessment of perceived exertion using the Borg scale. This scale ranges from 6 (no exertion at all) to 20 (maximal exertion) (Borg 1974). ◀

17.2.1.2 Selected Methods of Endurance Training

Various training methods are available for the development of endurance performance (◘ Table 17.1). More than one method should be used in practice to avoid monotony, and with increasing performance level, the full range should be utilised.

▪ Continuous Methods

Continuous methods are characterised by prolonged exercise at a constant intensity without interruptions (Schnabel et al. 2008). The extensive continuous method is defined by low to moderate intensity exercise lasting from 20 min to several hours. The main goal is to improve basic endurance and fat metabolism. Individuals returning to training or starting for the first time can use this method for adaptation to exercise load and to enhance endurance performance. In contrast, advanced athletes use this method to maintain their performance level or for mountain sport-specific training, such as a 12-h mountain tour with heavy equipment in preparation for an expedition. If a very low exercise intensity (max. 40% HRR) and a short duration (up to 30 min) are chosen, this method can also be used to support recovery, for example after intensive training phases or competitions. The intensive continuous method, on the other hand, aims to develop aerobic capacity and threshold performance. It is characterised by high intensity and a duration of up to 1 h (Schnabel et al. 2008).

Table 17.1 Selected endurance training methods and their corresponding intensity ranges (Mod. according to Garber et al. 2001)

Training method	% HRR	Perceived exertion (Borg scale)	Description
Continuous method (ext.)	40–60	12–13	Somewhat hard
Continuous method (int.)	60–80	14–17	Hard
Ext. interval method	70–85	15–18	Very strenuous
Int. interval method	≥ 85	≥ 18	Extremely strenuous
Fartlek method	40–85	12–18	Moderately to very strenuous

% HRR percentage of heart rate reserve; *ext.* extensive, *int.* intensive

- **Fartlek Method**

The fartlek method involves a “playful”, self-selected, and/or terrain-dictated variation in intensity. The fartlek method can include almost all intensity ranges, and the duration is up to 60 min (Schnabel et al. 2008). Accordingly, the potential objectives of this method are broad and include increasing the anaerobic threshold, improving maximal oxygen uptake, and enhancing lactate kinetics (Zintl and Eisenhut 2009). Thus, the fartlek method can be used in all training periods with an appropriate exercise structure.

- **Interval Methods**

Interval methods are characterised by a planned alternation of exercise and recovery phases (Zintl and Eisenhut 2009). The recovery phases should only allow partial recovery (“profitable break”). It is recommended that the recovery phase should last until the heart rate drops to 120–130 bpm (Schnabel et al. 2008). In the extensive interval method, high-intensity exercise should continue for 1–8 min. Usually, 6–15 intervals are performed, depending on the intensity. The aim includes raising the anaerobic threshold and increasing maximal oxygen uptake (Zintl and Eisenhut 2009). The intensive interval method is characterised by 3–10 exercise phases of 20–90 s each at very high intensity. The aim includes further developing maximal oxygen uptake in well- to highly trained individuals and training acid tolerance (Zintl and Eisenhut 2009). In endurance sports, intervals at near maximal or maximal intensities lasting several minutes are also performed in certain training phases to optimise maximal oxygen uptake (Dolci et al. 2020). However, this variant is only recommended for individuals who are highly accustomed to exercise and have a high level of performance and motivation. Although interval training is increasingly being used in clinical settings, these methods are typically applied by advanced athletes in mountain sports training.

17.2.1.3 Integration of Coordination Aspects into Endurance Training

In training practice, the warm-up phase can be used to develop coordination abilities. Technical drills such as heel kicks, high knees and/or skipping, bounding, skipping, or running with arm circles are suitable. In addition, balance can be developed through trail running (although there is a risk of injury!) or, for example, by wading through riverbeds.

17.2.1.4 Examples of Endurance Training Sessions

Training Using the Extensive Continuous Method (Mountain Hike)

Warm-up: relaxed walking with coordination exercises.

Main part (2–3 h): easy mountain hike with a rucksack at 40–60% HRR or a subjective perceived exertion of 12–13 on the Borg scale.

Cool-down: relaxed descent followed by loosening and stretching exercises.

Training Using the Intensive Continuous Method (Mountain Walking with Poles)

Warm-up: relaxed walking at low intensity. The terrain can be used for balance exercises (e.g. balancing on stones or roots).

Main part (approx. 30 min): intensive uphill walking with the use of poles. Intensity 60–80% HRR or 14–18 on the Borg scale.

Cool-down: relaxed descent.

Training Using the Fartlek Method or Extensive Interval Method (Running in Terrain or Steep Ascent)

Warm-up: relaxed walking or running.

Main part, fartlek method (approx. 40 min): running with varying intensity due to changes in speed or terrain. Intensity: 50–80% HRR or 13–17 on the Borg scale.

Main part, extensive interval method (approx. 40 min): 4-min steep ascent with a heavy rucksack at 75–85% HRR or 16–18 on the Borg scale. Relaxed descent until heart rate drops to 120–130 bpm, then repeat the intensive ascent; a total of six intervals.

Cool-down: relaxed walking or running.

17.2.2 Strength Training

17.2.2.1 Intensity Regulation in Strength Training

The training intensity can be estimated as a percentage of the “one-repetition maximum” (1-RM). The 1-RM should be determined when warmed up and, for safety reasons, with a training partner. Starting at approximately 50% of the expected maximum weight, perform one correctly executed repetition with this weight. If this is possible without assistance, after a 3–5-min rest, increase the weight by 5–10%. This process is repeated until the weight at which only one repetition with correct technique and full range of motion is possible; this weight represents the 1-RM (American College of Sports Medicine 2022). Alternatively, and particularly for exercises where weight adjustment is not possible, the weight should be selected so that the number of repetitions appropriate to the training method can just be completed.

17.2.2.2 Selected Strength Training Methods

There are many methods in strength training. The strength endurance method and a hypertrophy method are presented here.

Strength Endurance Method

This method aims to maintain a specific level of strength performance over an extended period. Strength endurance training can be efficiently performed as a circuit. The exercises are performed consecutively with only short breaks (20–60 s). Depending on training status, the circuit can be repeated 1 to 3 times, with a rest of 3–5 min between rounds. The strength endurance method is characterised by the following parameters (adapted from Schnabel et al. 2008):

- Number of repetitions: 20–40 (or duration of 1–2 min).
- Intensity: 40–60% of 1-RM or such that 20–40 repetitions (or 1–2 min) to exhaustion are possible.

Hypertrophy Method

Training using the hypertrophy method leads to a long-term increase in muscle mass, which is associated with greater maximal strength. Although, with few exceptions, maximising muscle mass is not desirable in mountain sports, hypertrophy training nevertheless forms a foundation for achieving or maintaining a certain strength level (e.g. for steep ascents with heavy additional weight). An appropriate method is station training, i.e. a specific exercise (e.g. bench press) is completed with one (single-set training) or several sets (multiple-set training) before moving on to the next exercise (e.g. pull-ups). In the long term, multiple-set training is likely to result in slightly greater strength gains compared to single-set training, while the advantage of single-set training lies in time efficiency (Fröhlich et al. 2010). The loading parameters for the hypertrophy method are as follows (based on Schnabel et al. 2008):

- Number of repetitions: 8–12
- Intensity: approx. 80% of 1-RM or such that 8–12 repetitions to exhaustion are possible
- Sets: One set for single-set training (to exhaustion, for advanced individuals possibly two–three additional repetitions with partner assistance); two–three sets for multiple-set training

17.2.2.3 Integration of Coordination Aspects into Strength Training

Training of balance and stabilisation can be combined with strength training by performing the respective exercises on an unstable surface. This is particularly suitable for lower limb exercises (e.g. squats) and core stabilisation exercises (e.g. forearm plank), but upper body muscle training (e.g. push-ups) can also be varied in this way. Suitable unstable surfaces include gym mats of varying thicknesses (possibly doubled) or, for certain exercises, exercise balls.

17.2.2.4 Examples of Strength Training Sessions

For general strength training, a session should include 6–10 exercises for the core, lower limbs, and upper body (chest, back, and upper limbs). Movements should be performed in a controlled and slow manner; a training partner can provide support and motivation. The following examples each represent just one possible training session, which should be adapted to individual circumstances (e.g. training status) and available facilities (gymnasium, fitness studio, etc.).

▪ Training Using the Strength Endurance Method

Warm-up: Aerobic exercise to music.

Main part (approx. 35 min): Circuit training with six stations, slow execution of movements, 2 min per exercise, 30 s rest with change to the next station, two rounds with 4 min rest in between:

- Exercise 1 (upper body): Push-ups or wall push-ups (easier version).
- Exercise 2 (lower limbs): Supine position with hips raised and lower legs on an exercise ball, exercise ball is pulled towards the glutes by bending the knees.
- Exercise 3 (core): Abdominal crunches in supine position.
- Exercise 4 (upper body): Seated row with Thera-Band.
- Exercise 5 (lower limbs): Lunge squat with the front foot on an unstable surface, possibly with additional weight using a dumbbell or medicine ball (or similar), train both sides.
- Exercise 6 (core): In prone position, alternately lift one arm and the opposite leg slightly.

Cool-down: Light jogging on the spot and relaxation of the trained muscles.

- **Training Using the Hypertrophy Method with Dumbbells and Exercise Machines**

Warm-up: Rowing ergometer.

Main part (approx. 45 min): Station training with six exercises (multiple-set training), slow execution of movements, 10 repetitions per exercise, three sets each with 2 min rest in between:

- Exercise 1 (upper body): Bench press with barbell
- Exercise 2 (lower limbs): Leg press
- Exercise 3 (core): Back extension machine
- Exercise 4 (upper body): Lat pulldown
- Exercise 5 (lower limbs): Lying or seated leg curl on machine
- Exercise 6 (core): Hanging leg raises on wall bars

Cool-down: Cycle ergometer followed by relaxation exercises.

17.3 Ascent Strategy

Many factors influence a mountaineer's performance in the field, not just training status. Ascent strategy has a significant impact. Other elements such as nutritional behaviour and acclimatisation strategies, which are addressed in ► Chaps. 18 and ► 19, can also influence outcome. In this chapter, a few selected aspects of walking and climbing strategies are discussed.

17.3.1 Walking and Climbing Pace

The walking and climbing pace should be determined by the individual performance capacity of the group members as well as the difficulty and length of the route. During the first 30 min or so a slow pace should be chosen, especially if there is initially steep terrain, as there is a risk of a significant increase in lactate, which can also inhibit long-term energy supply from fatty acids (Astrand et al. 2003). The consequences are early depletion of glycogen stores and premature fatigue.

After the warm-up phase, the pace can be adjusted to the individual performance level. The pace should be set so that the exertion can be maintained continuously without breaks and without a significant sense of effort. The pace must be adapted to the terrain conditions (steepness, path quality, etc.). As a guideline for exercise intensity, normally trained individuals can sustain an intensity of no more than 60% of VO_2 max (corresponding to 60% HRR) over a prolonged period (Burtscher 2004; American College of Sports Medicine 2022).

> ❯ On group tours, the pace should be set according to the member with the lowest performance capacity.

Choosing the correct walking and climbing pace also means ensuring that energy reserves are kept for the descent, as this also places considerable demands on physical fitness (see ► Sect. 17.3.2).

- **Structuring Breaks**

Breaks primarily serve to aid recovery after intense exertion (e.g. trail-breaking in snow, traversing scree slopes), to replenish depleted energy stores (eating), to compensate for fluid loss (drinking), and, if necessary, to adjust clothing to ambient conditions. For practical reasons, breaks should only last as long as needed to accomplish these activities. Exhausting efforts that require a longer break should be avoided, as mentioned above, as they may jeopardise the successful and accident-free completion of the tour. It is advisable to take a longer break before the descent. Usually it is preferable to do this in sheltered terrain (not necessarily on the summit) to avoid "cooling down".

17.3.2 Going Downhill

Going downhill demands specific physical and coordination abilities. Oxygen uptake and thus energy expenditure during descent are lower compared to ascent (Minetti et al. 2002). However, there is predominantly eccentric exercise of the lower limb muscles and relatively high stress on the joints, which often leads to muscle and joint pains. In addition, these stresses often occur when individuals are already fatigued and where difficult terrain puts high demands on balance and body stabilisation. It is therefore understandable that more than half of all hiking accidents occur during descent (Faulhaber et al. 2017). For this reason, the choice of walking and climbing pace and the structuring of breaks as previously mentioned are of great importance for accident and injury prevention.

It is important when descending to walk slowly and take small steps to reduce peak forces on the joints and muscles. Fast descents with large steps and jumps, etc., carry an increased risk of falls and injuries and should, if at all, only be attempted by specifically trained individuals who are not fatigued. Regular short breaks should also be considered during descent to allow the muscles some recovery from unfamiliar strain.

Proper use of poles can reduce the load on the lower limbs and increase stability (Bohne and Abendroth-Smith 2007; Jacobson et al. 1997). However, it has also been shown that a large proportion of mountain hikers do not use poles correctly (Haid and Koller 1995).

The muscle soreness is characterised by muscle pain and loss of strength. These symptoms occur particularly at the beginning of the season after the first mountain tour (after an unusually long descent). Studies have shown that after experiencing muscle soreness, a phase follows in which muscle pain after descending occurs to a lesser extent—however, muscle strength remains reduced (Chen and Hsieh 2001; Pierrynowski et al. 1987). This is particularly important when planning and organising multi-day tours or repeated day trips (e.g. during holidays).

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Nutrition for Mountain Hiking and Mountaineering

Volker Veitl

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18.1 Introduction

Both long-term and short-term nutrition are directly related to health and performance. Nutrition is one of the fundamental factors for good performance. Nutritional quantity and quality are the basis for achieving sporting goals. With the start of special physical activities, there must be a good basal nutritional status that is then adapted to the new physical requirements, in both the short term and long term. A wholesome diet is the basis for preparing for an adapted diet for a tour to high altitude.

The more intense and the longer the physical demands, the more an inappropriate diet has unfavourable consequences in terms of a performance reduction, and in health impairments and diseases. Wholesome nutrition, wholesome food and drink ensure health, promotes performance and well-being. To implement a wholesome daily diet, the German Society for Nutrition (DGE) has formulated ten rules for the average population based on current scientific findings. These are the basis for adapting an athlete's diet to his or her individual requirements.

In mountaineering circles, optimal nutrition is often equated with quantity rather than quality because of the high physical exertion. For example, according to anecdotal reports, the legendary Viennese mountaineer Karl Lukan is said to have described "a Gulyas (goulash) and a nice pork roast and a beer with it" as good mountaineering food.

Nowadays, an understanding of optimal daily nutrition has certainly advanced and is based on published and scientific dietary guidelines. The abundant supply of special supplements to achieve individual sporting goals shows that interest has been aroused. However, there are still no established rules or guidelines for the needs of athletes or mountaineers. To fully meet the needs of nutrition in alpine sports, individual assessment and planning must be carried out for general daily activities and for the special challenge.

Physical performance has long-term and short-term components: Long-term nutrition serves the physical and mental development to cover the energy and nutrient requirements for everyday activity and to prepare for the physical demands of sporting activities or mountain tours. It extends over at least months and years. Short-term nutrition must quantitatively and qualitatively cover the demands during the exertion of the sporty mountain tour and be individually adapted to the altitude of the activity. The period for this is a maximum of several weeks. Deficits that impair performance and concentration (water, energy, active ingredients) must be identified and quickly remedied to avoid acute health risks. Those inexperienced in mountain sports often underestimate the effects of appetite loss at altitude, of hunger and thirst.

18.2 National and International Societies for Dietary Recommendations

The dietary recommendations published by the WHO (World Health Organisation), FAO (Food and Agricultural Organisation), or DGE (German Nutrition Society) are based on reference values for energy and nutrient intake for different age groups of the respective population group (e.g. DACH: Germany, Austria, Switzerland). A needs-based diet is achieved under average living conditions with the aim of preventing diet-related diseases and promoting sustainable diets (WHO 1998; DGE 2017, 2018, 2024; Cunningham-Rundles et al. 2005). The dietary recommendations are regularly revised and aim to reduce the consumption of food groups which are associated with the development of diet-related diseases or that have a harmful environmental or climate effect (greenhouse gas emissions and land use) (DGE et al. 2015). The wholesome diet, according to the DACH guidelines, can help promote growth, development, performance, and health throughout life. In addition, the diet can eliminate or minimise risk and prevent the oversupply of a food type.

The DACH reference values (DGE 2018) aim to ensure an adequate intake of nutrients, energy, water, and fibre for the normal healthy population, but without always requiring detailed needs calculations. A moderately increased intake is considered to create body reserves for a small increase in demand. However, requirement values for special training, above-average performance, or an extreme mountain tour are not included in the reference values. Thus, athletes must develop their individual nutritional plans based on their goals for performance.

18.3 General References for Energy and Nutrient Intake

For healthy people in the average population, the reference values are intended to ensure vital mental and physical functions and avoid unnecessary health risks. In addition, body reserves are created to bridge short-term increases in demand and to achieve preventive effects. Competitive sports are not included! DACH reference values, to specify energy and nutrient quantities for the average daily intake of different population groups, are divided into different categories: Recommended intake, estimated values, and guideline values as defined below (DGE 2018):

- Recommended intake: Scientifically proven values for the daily nutrient intake of proven significance (e.g. protein, linoleic acid, many vitamins and minerals).
- Estimates: Nutrient requirements are not known with sufficient precision (e.g. o-3 fatty acids, vitamins E and K). Bodily demand cannot be determined with desirable accuracy.
- Guideline values: Recommended nutrient intake for which no confirmed requirement can be cited (e.g. energy, water, fluoride, fibre, fat, cholesterol, table salt). They result from experience and indicate scientifically unproven areas and serve as a consensus approximation.

The reference values do not have to be met daily or in an individual meal. They are an average to be taken over a week. Because of reduced absorption rates of various nutrients when given in high doses, the intake should be even and not as a single high dose. This must also be considered for sports-specific supplements! So, 2 to 3 times a day a lower dose is better and, ideally, half an hour before a meal with a glass of water or 2–3 h afterwards!

Absolute, exact, individual demand values cannot be calculated with the reference values. Individual needs depend on many physiological influences (age, sex, nutritional status, health, etc.) and can be influenced by external influences (climate, altitude, physical activity)! The use of the DACH guideline values to calculate the individual requirement provides a general security, but the necessary intake must be estimated separately for individual life circumstances such as special training to improve performance!

Based on current scientific findings, the DGE has formulated 10 rules for wholesome eating and drinking. These are also considered the qualitative basis for long-term nutrition to promote performance in daily life (DGE 2017, 2024, 2024):

1. Enjoy Food Diversity
   No food alone contains all the essential nutrients that promote health and performance. A mixed diet and a dominant plant-based diet have been proven to have a preventive effect.

2. Vegetables and Fruits—"Take 5 a Day"
   Five portions of fruit and vegetables every day that provide an abundant supply of vitamins, minerals, dietary fibre, and secondary plant substances are ensured, which promote the metabolism, the immune system, and the intestinal flora. The fruit should be as fresh as possible and the vegetables not intensively cooked. For the average person, about 400 g of vegetables and 250 g of fruit are recommended daily. The energy requirement in high-performance alpine sports will necessitate larger portions.
3. Choose cereal products and potatoes as favourable sources of carbohydrates.
   Whole grain products (bread, cereal flakes for muesli, pasta, rice) and fresh potatoes (boiled or baked potatoes) contain plenty of vitamins, minerals, fibre and secondary plant substances, and significantly more than in white flour products. The preparation should be carried out gently and without fat.
4. Supplement your diet with low-fat animal foods
   Daily low-fat dairy products (milk, kefir, quark, yoghurt with bifidus cultures and 1.5% fat, cheese with 30% dry matter), fish (salmon, mackerel, herring), and lean meat (2–3 times a week) provide readily available protein and other valuable nutrients.
   For the average energy requirement, about 150 g of dairy products per day and 300–600 g of meat or fish per week. Marine fish (free-living or well-nourished) provides valuable long-chain fatty acids (eicosapentaenoic acid [EPA], docosahexaenoic acid [DHA]) in addition to protein.
5. Use health promoting fats.
   Fats are the dominant source of energy. Vegetable fats and oils should be preferred; they also provide plenty of essential unsaturated fatty acids and vitamin E. These reduce the risk of high blood lipids, coronary heart disease, and hypertension. Rapeseed and olive oil are top choice as they provide vital omega-3-fatty acids (o-3FAc), docosahexaenoic acid (DHA), and the necessary vitamin E. Sunflower oil can be used for frying, but it should not be consumed. Margarine and butter are unnecessary for a wholesome diet! You can also make a "jam bread" with curd cheese or cream cheese (cottage cheese)! Coconut oil, palm oil, and animal lard have an unfavourable profile with regard to health, and fried fat out of the pan should be thrown away!
6. Saving sugar and salt
   High-sugar and salty foods are not appropriate for a wholesome diet. The general carbohydrates (starch products, maltodextrin) are necessary for physical performance.
   If salt is used, then only iodinised salt and a maximum of 6 g/day (1 level teaspoon per day). You can also cover your iodine needs with sea fish. Instead of salt, it is better to season with herbs. Information on sugar and salt content can be found on food packaging in the list of ingredients and nutritional table!
7. It is best to drink water
   To cover the daily requirement of fluids during low physical exertion periods, 1.5–2 l of water is sufficient. Ideal thirst quenchers are water, unsweetened herbal or fruit teas. You can add flavour to drinking water by letting it stand a little longer with herbs (mint, sage, rosemary) and flavouring it. Lemonades, cola, or industrial fruit juice drinks usually contain a lot of sugar and few nutrients in relation to the energy content (nutritional table on the label). For competitive athletes, who have a high need for fluids and minerals due to their sweat losses, the "lemonades" are not recommended.
8. Prepare gently
   In principle, cook the food for as short a time as possible, with little fat or

water. The less and the shorter the heat is applied, the more nutrients are retained. The "water bath" in the saucepan dissolves many vitamins and minerals. The cheapest way to cook vegetables is with steam or in the microwave with a short heat.

9. Mindful eating and enjoyment
   If you eat too fast, it is easy to overlook the fact that too much is being consumed. The feeling of satiety only occurs 15–20 min after eating! So small bites and chew patiently!
10. Pay attention to your body weight and keep moving
   Nutrition and exercise, wholesome nutrition, and daily physical activity belong together. 5000–10,000 steps or 30–60 min of cycling per day (or as a daily average per week) are recommended. Competitive athletes will do enough meaningful exercise with their regular training.

Detailed qualitative and quantitative information on a wholesome diet for different population groups can be found on the homepage of the German Nutrition Society (► www.dge.de) (DGE 2017). Special brochures are also offered. However, the DACH dietary recommendations must be individually modified for competitive athletes and alpine athletes!

18.4 Daily General Dietary Requirements

The wholesome food, according to DACH guidelines, makes a significant contribution for promoting the metabolism and optimising the immune system. The effectiveness of the individual immune system depends significantly on dietary factors. Excessive sweet carbohydrates (glucose, fructose, sucrose) or sweeteners, high intake of saturated fatty acids, emulsifiers, high salt content have a negative influence on the intestinal microbiome and negate its significant positive influence on the entire immune system.

Insufficient nutrition, especially malnutrition, is accompanied by disorders of the innate as well as the acquired immune system. Qualitative malnutrition is detrimental by affecting the building blocks and regulatory factors of the immune system (Cunningham-Rundles et al. 2005).

The most common problems are undersupply and deficiencies of iron, iodine, vitamins A, B12, D, and zinc. Furthermore, the general diet usually lacks the secondary food ingredients that promote a healthy intestinal flora. The ecosystem of the gut microbiome is essential for the immune system, brain, organs, and metabolism.

There are many more than a 1000 different bacterial species (intestinal microbiome) that a person carries in their intestine. Each person has a unique profile. The gut microbiome contains millions of genes for bioactive substances that produce enzymes and thousands of metabolic substances (Qin et al. 2000) that influence metabolic processes and the immune system.

Bacterial mis-colonisation of the intestine increases intestinal permeability and causes chronic inflammation. Plant-based mixed foods (fruits, vegetables, and salads) provide a higher number and amount of secondary plant ingredients (prebiotics, e.g. flavonoids, phenolic acids, carotenoids, phytoestrogens), which have favourable antioxidant and immunomodulating properties. Significantly lower concentrations of inflammatory markers in the metabolism (e.g. CRP, fibrinogen) and a decrease in leukocytes were observed with a vegetarian diet compared to a usual non-vegetarian mixed diet (Craddock et al. 2019).

18.5 Nutrition for Gut Health and Gut Microbiome

The composition of the intestinal microbiome can be easily changed by short-term changes in diet and this shapes its structure and functions. A low-fibre Western diet can lead to the loss of individual bacterial species that limits the functions of the intestinal microbiome. Low consumption of plant-based foods is accompanied by a low degree of inflammation in the body, which results in damage to the intestinal barrier. Dying bacteria form endotoxins, and they pass through the damaged intestinal mucosa and cause endotoxaemia.

In the case of a stay of several weeks in a changed environment, a supply of beneficial intestinal bacteria (probiotics), foods that promote intestinal bacteria (prebiotics, Mediterranean diet), and appropriate dietary supplements (e.g. unsaturated fatty acids [EPA, DHA], flavonoids, reservatol, quercetin, soluble and insoluble dietary fibres, vitamins A, E, D, trace elements such as iron, zinc, selenium) are necessary to reduce the risk of bacterial mis-colonisation (Mc Farland et al. 2018).

An undersupply of vitamin D (blood <50 nmol/l; 20 ng/ml) is associated with high levels of inflammatory markers. Significantly lower inflammation levels (TNF-α, IL6, CRP) were found with vitamin D substitution (Givenzi et al. 2023).

Polyphenols from plant-based foods are known to have an antibiotic effect on pathogenic intestinal germs. They also have a prebiotic effect and promote the development of beneficial intestinal bacteria (Bifidobacteria, Lactobacillus, Saccharomyces, A. muciniphila). Foods with fermentable dietary fibres (e.g. pectins, inulin, β-glucans) and prebiotic oligosaccharides (GOS, FOS) also offer the opportunity to contribute to the development of a protective intestinal flora. The most important foods to provide this fibre are apples, carrots, asparagus, parsnips, chicory, onions, oatmeal, whole grain products, mushrooms, legumes (garden beans, peas, chickpeas, lentils, soybeans)!

A diet with a low-fibre content reduces the function of the CD+ T cells of the adaptive immune system and thus causes an immune deficiency. Body immunity can be increased again in a short time by eating a diet containing fibre. Regular, weekly fibre-providing nutrition with different foods or dietary supplements is necessary for the immune system in the case of disturbed whole food nutrition (Siracus et al. 2023)!

The intensive “modern” diet with its high proportion of processed foods, “high” standard of hygiene, and low consumption of unheated foods leads to an intestinal flora with less favourable bacteria, a reduction in the diversity of the microbiome and thus to unfavourable influences on the metabolism and immune system. Fermented foods (e.g. sauerkraut, bifidus yoghurt, acidophilus drink, kefir, kimchi, miso) and probiotics can redress the balance. Diarrhoeal diseases also have a very unfavourable effect when travelling. These events inevitably require a simultaneous and subsequent supply of probiotic foods and/or probiotic supplements for several weeks. These measures must be carried out for at least 2 weeks to restore a favourable intestinal flora.

A negatively impaired gut microbiome can be significantly corrected within 24 h by probiotics with a favourable, rich bacterial spectrum, and prebiotic nutrient sources (fibre-rich foods, GOS, FOS) in a relatively short time.

The bacteria in fermented probiotic foods (e.g. Bifidobacterium, Lactobacillus, Saccharomyces) compete with other intestinal bacteria for nutrients and binding sites at the mucosa in the intestine. Their metabolites (short-chain fatty acids, antimicrobial peptides) then inhibit the growth of pathogenic germs, and the beneficial intestinal flora is revived. Several Lactobacillus strains (L. acidophilus, L. casei, L. rhamnosus, L. reuteri, Streptococcus thermophilus) have been successfully used as a prevention of antibiotic diarrhoea or traveller's diarrhoea (Mc Farland et al. 2018).

The probiotic food supplements used must have the highest possible concentration of germs per dose to effectively reach the large intestine. They should be taken on an empty stomach, at least 30 min before the next meal with plenty of water, and protected from denaturation by stomach acid. When probiotic supplements are used orally, they have been observed to lower proinflammatory cytokines and increase anti-inflammatory cytokines (Huber et al. 2021).

For trips abroad, with possible supply problems with wholesome mixed foods, it is necessary to secure the intestinal flora and thus the immune system with probiotic food supplements.

18.6 Nutritional Requirements in Mountain Sports

There are no scientifically recognised guidelines for nutrition in alpine sports yet. The diet in mountain sports must be individually adapted differently based on the DACH reference values, in a similar to that for competitive athletes, and from "mountain fans" to alpine athletes. This refers to the multiple, simple mountain hike every year to the mountain performance athlete who undergoes regular weekly training and adapts his physical development to the demands of a tour lasting several weeks at high altitude.

Annual requirements by the special training-related lifestyle are subject to different conditions than the high mountain tour lasting several weeks. The most important nutritional considerations for the mountain tour include the high energy and fluid requirements, the necessary protein and carbohydrate supply to prevent loss of muscle mass, the need for antioxidant foods to maintain the effective immune system and iron supply to stabilise erythropoiesis and oxygenation.

On a mountain hike up to an altitude of about 1500 m, there are usually no health impairments, and the daily whole foods remain as usual. For a short tour (≤1.5 h) to medium altitudes up to about 2500 m, an immediate adjustment with a drink and a carbohydrate-rich snack is sufficient.

The prolonged stay at altitudes above 2500 m and up to extreme altitudes brings many physiological challenges. The variant of "high-altitude mountaineering" leads to significantly reduced air pressure at altitudes of about 5000 m and requires a physical adaptation to the reduced oxygen supply at altitude and special nutrition planning for the longer physical exertion. Here, nutrition must be planned for a longer period for good acclimatisation.

In addition to the influence of altitude on physical and cognitive functions, a negative energy balance often occurs, leading to weight loss, changes in body composition, and loss of performance. In particular, the breakdown of lean body tissue is associated with performance, safety and health risks. To reduce this, in addition to the basic wholesome diet, it is important to reduce the predominantly activity-related additional need for energy, carbohydrates, protein, active ingredients, and fluids.

The DACH reference values are based on the body weight and body composition of the average population groups. In accordance with these, the individual energy and nutrient requirements of the competitive athlete for his daily activities and for a longer alpine tour must be modified to his anthropometric (lean body weight), physiological, training, and gender-specific parameters. Above 5500 m, however, a complete adjustment to the altitude is no longer possible. Here, physical and mental deterioration occurs during a longer stay. Therefore, only short-term stays can be maintained.

18.7 Energy Requirements in Competitive Sports

Energy demand is not a fixed quantity. It is influenced by body weight, body composition, physical activity, growth, with physical activity being the most variable component.

With the total food energy (E), all the main nutrients are absorbed when eating normal food. Protein is said to provide 12–15% of E, fat 30–35% of E, and carbohydrates the main share with 50–55% of E. For athletes, the individual resting energy expenditure, the need for usual daily activity, and the requirement for the specific sporting performance must be added together to calculate the daily energy consumption. The total sum depends on current body weight, body composition, gender, age, state of health, ethnic origin, location, and ambient temperature, but very much on the amount of physical activity.

Meeting the energy and nutrient requirements at high altitudes is a huge challenge. Some research shows an undersupply of 20% or more, which leads to the loss of lean body mass. This negatively affects aerobic capacity, muscle strength, impairs the body's immune functions, and stimulates the triggering of altitude sickness.

At high altitudes, appetite, hunger, and satiety are reduced, and thus energy intake is greatly reduced without diet planning. For this reason, a 30–50% decrease in energy intake at high altitude is reported. After acclimatisation at a high base camp, appetite generally improves, but at a high altitude (>5000 m) appetite continues to decrease and is closely associated with the occurrence of acute altitude sickness (AMS).

Experience in the mountains can have a beneficial effect on a wholesome diet. Nutrition planning with daily menus for longer high mountain tours is necessary during the training period and brings safety. The loss of lean body mass (mKM) associated with the negative energy balance negatively affects the body's aerobic capacity, muscle strength, and immune functions at high altitudes, increasing the risk of disease (AMS) and injury in these extreme conditions.

The estimation of the loss can be determined with a skin fold measurement. A scale with BIA (body impedance analysis) to determine body composition does not show correct values for lean body mass (mKM) because of possible dehydration. To estimate the individual energy requirement, the optimal body weight is to be determined, which depends on the body size, but is very different from the athlete and the competitive athlete in the average population and depends strongly on the longer amount of training. Ideally, a weight with a body fat percentage of 15% (male) to 25% (female) should be used for the calculation. For calculations, it therefore makes more sense to use the weight before the start of the mountain tour, or at the latest from the base camp, for nutritional need assessments. As a base value for the athlete's nutrition planning, body fat determination, e.g. with skin fold measurement or BIA, should be carried out before exercise.

Depending on the sport, male and female athletes have different amounts of body fat. For example, studies of female track and field athletes show an average value of 18% body fat (16.2–19.8%) and male colleagues 10.4% (9.5–11.4%). For volleyball players (similar values for basketball players), 25.6% body fat (23.1–28.1%) was found for female athletes and 14.3% (12.6–16.1%) for male athletes (Santos et al. 2014). This results in a clear difference in resting energy expenditure for athletes and non-athletes at the same weight.

A body composition with low fat mass and high proportion of lean mass (lean body weight, mKG) correlates with higher cardiorespiratory fitness and higher performance. The optimal weight for nutrition planning is the one at which the best training and/or competition results have been achieved and where the body fat does not significantly exceed 15% (m) or 25% (w). The same orders of magnitude can also be adopted for alpine sports. Gender, lean body weight (mKG), and age are used to calculate resting energy expenditure.

Calculation of Resting Energy Expenditure (REE) (DACH 2015)

REE is given in kcal per day (kcal/d) or in kcal per weight and hour (kcal/kgh).

- **Women: REE = (0.047 × mKG kg – 0.01452 × Age [years] + 3.21) × 239**
- Example 1:

Woman, 60 kg, 40 years:

REE = (0.047 × 60–0.01452 × 40 + 3.21) × 23 9.

= (2.82–0.5808 + 3.21) × 239.

= 1302 kcal/d.

REE = 0.90 kcal/kgh.

- **Men: REE = (0.047 × mKG kg + 1009–0.01452 × Age [years] + 3.21) × 239**
- Example 2:

Man, 71 kg, 40 years:

REE = (0.047 × 71 + 1009–0.01452 × 40 + 3.21) × 239.

= (3337 + 1009–0.5808 + 3.21) × 239.

= 1667 kcal/d.

REE = 0.98 kcal/kgh.

The REE, the largest contributor to daily energy needs, represents the energy needed to support the maintenance of normal body function and homeostasis at rest. It usually accounts for 60 to 80% of the total energy demand of the average population. This basal energy expenditure (BEE) is closely related to lean body mass. It has a metabolic rate of 20 kcal/kg and adipose tissue only 5 kcal/kg.

To estimate the energy requirement for physical activity, the average heart rate (HR) during the duration of activity and at rest (relaxed lying) can be used. With a heart frequency clock or heart rate monitor, the HR can be determined for different activity periods and applied for calculation of the daily energy requirement.

If the activity heart frequency (AHF) is divided by the resting heart frequency (RHF), the "Physical Activity Level" is obtained, the PAL value, by which the individually calculated resting energy (REE) for the duration of the activity is multiplied, and thus the energy consumption for the controlled activity time is calculated (see Example 3 and ▣ Table 18.1).

- Example 3: See Table 18.1

Amateur athlete male, 71 kg, 40 years

REE 24 h	(RHF 60)
Training 3 h	(AHF 140)
Sleeping 6 h	(SHF 50)
Daily activity 15 h	(AHF 90)

The measurement of daily heart rates during the usual training for 3 days up to a week or even during the stay on the mountain at different altitudes makes it possible to estimate the individual energy requirements, which provides the basis for nutrition planning under the measured conditions. The calculated REE per hour, multiplied by the PAL value and the duration of activity, results in the energy requirement for the activity with the registered heart rate (AHF).

For intensively training alpine athletes, it is necessary to carry out the individual requirement calculation based on HF measurements and not only to use the DACH energy recommendation, as the trained body does not correspond to that of the average population.

The DACH reference was developed for a body mass index (BMI) of 22 kg/m^2!

$$BMI = \text{weight}(\text{kg}) / (\text{height}(\text{m}) \times \text{height}(\text{m})). BMI = \text{kg}/\text{m}^2!$$

▪ **Table 18.1** Calculation example for energy requirements during physical activity (Example 3)

	Duration (h)	**PAL (AHF/RHF)**	**Energy (kcal)**	**HF n/min**
Resting energy	24		1667	60
Activity training	3	2.33	486	140
Activity normal	15	1.50	1563	90
Sleeping	6	0.83	347	50
Day energy sum	24		2396	
Day energy average	24	1.44	2396	86

HF n/min heart frequency/Min, *RHF* resting heart frequency, *AHF* activity heart frequency, *PAL* physical activity Level, *SHF* sleeping heart frequency

For athletes, this BMI is not valid because of the above-average lean body mass (muscle mass) and usually lower body fat mass in relation to body weight. Therefore, individual energy estimation with heart rate and determined lean body weight by weight and body fat measurement makes more sense with a balanced body water balance.

▪ Table 18.2 provides estimates of the energy requirements for persons with different levels of physical activity according to the DACH recommendation, separated into women and men, various age groups, and different levels of physical activity. With increasing age, the energy requirement decreases at a comparable intensity of physical activity due to the assumed reduction in muscular body mass.

For development of own energy supply that the alpine athlete should use before the extreme mountain tour, the heart rate method (heart frequency) with a comparable training tour plan in his usual training area. Based on the resting HF (and, possibly, also sleep HF) in the valley and the average frequency rate for an ascent to about 2500 m, up to 3500 m and above, resting HFs at altitude and for each stage, the time required must be calculated.

With the valley resting HF and the activity HF, the PAL values and the energy requirement for the different tour stages can be calculated, which can then added up to give the daily energy requirement (▪ Table 18.1).

This provides the basis for an individual quantitative nutrition plan. This can then be implemented by a nutritionist or, after their own further training, into an individually adapted nutrition plan for the tour, which is structured according to the DACH dietary recommendations for a wholesome diet.

Table 18.2 DACH guideline values for energy intake during various physical activities (PAL index)

Age groups	DACH guideline values for the energy intake of adults during various physical activities (PAL = physical activity level; PAL = HFActivity/HFRest) in kcal/day					
	PAL- 1.4		PAL- 1.6		PAL- 1.8	
	m	w	m	w	m	w
19 to <25 years	2400	1900	2800	2200	3100	2500
25 to <51 years	2300	1800	2700	2100	3000	2400
51 to <65 years	2200	1700	2500	2000	2800	2200
> 65 years	2100	1700	2500	1900	2800	2100

PAL value = activity level:

– 1.2: sedentary or lying lifestyle

– 1.4–1.5: Sitting work only, less strenuous leisure activity, e.g. office workers

– 1.6–1.7: Sitting work, temporary additional energy expenditure, walking or standing activity, e.g. laboratory technicians, drivers, assembly line workers

– 1.8–1.9: Predominantly walking and standing work, e.g. housewives, nursing staff, waiters, mechanics, craftsmen

– 2.0–2.4: Physically demanding professional work, e.g. construction workers, farmers, forest workers, competitive athletes, miners

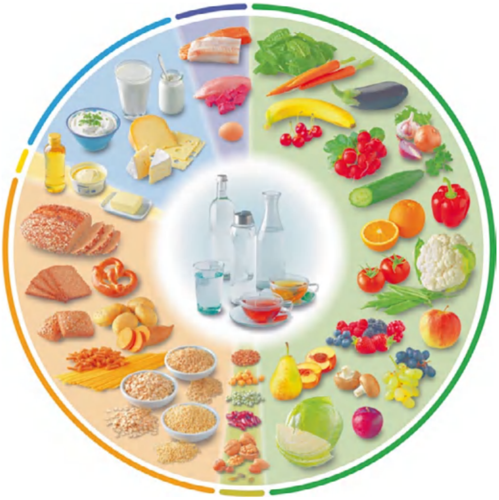
For regular physical activity (30–60 min of exercise/day), about 0.3 PAL is added.

HF heart frequency

18.8 Implementation of Dietary Recommendations in Daily Performance-Based Nutritional Practice

The scientifically coordinated DGE recommendations are useful as a wholesome diet for alpine and competitive athletes in their daily diet. However, special situations, e.g. targeted special muscular development, special endurance, or prolonged stay at high altitudes, require targeted changes in diet to achieve a wholesome diet suitable for training and touring.

The 10 DACH basic rules (see ▶ Sect. 18.3) for a whole food diet are graphically implemented in a nutrition circle (◘ Fig. 18.1). This represents the necessary (and less



◘ **Fig. 18.1** DGE Nutrition Circle (DGE-Ernährungskreis) necessary) food groups with its sector sizes (▶ www.dge.de/gesunde-ernaehrung) (◘ Fig. 18.1, ◘ Table 18.3).

> The carbohydrate supply is provided by foods from groups 1 and 2 (◘ Table 18.3)! Black and green tea, herbal and fruit tea are cheap, but beer and wine are only stimulants! They are said to contribute insignificantly to the energy supply. Only before and/or during high physical exertion, use special carbohydrate drinks or carbohydrate-rich foods and additional water to drink.

> The realisation of a wholesome diet is often associated with the development of new eating habits.

◘ **Table 18.3** Recommended energy percentages (E%) of the food groups in the DGE nutrition circle

Circle group	Foods	Part of energy intake
1	**Cereals, whole grain cereal products** Whole grain flours, cereal flakes, bread and baked goods, pasta, brown rice, buckwheat, quinoa, amaranth, potatoes! Whole grain foods in this group are an important source of carbohydrate energy and provide high-quality protein, vitamins, minerals, fibre, and phytochemicals	Approx. 31%E
2	**Vegetables, legumes, and salads** The foods in this group are essential for the important supply of nutrients, fibre, carbohydrates, and important secondary plant substances! Legumes offer valuable proteins that complement animal foods to form an optimal protein mixture (higher protein value for metabolism)!	Approx. 25%E
3	***Fruits, berries, nuts*** Rich in important nutrients, secondary plant substances,but unfavourable fat Fruit is an important part of the whole diet with plenty of vitamin C and ß-carotene, as well as secondary plant substances (prebiotics) and fibre Nuts contain little water, but at the same time plenty of unsaturated fatty acids and protein 25 g of nuts correspond to about one serving of fruit!	Approx. 17%E
4	*Milk and dairy products (without butter) with a low-fat content(≤1.5% FDM, fat in dry mass)* They contain high-quality, indispensable protein for muscle building and supply In addition, they provide vitamin B2 and calcium Low-fat variants(milk and yoghurt 1.5% FDM, cheese 30% FDM mass) are preferable!	Approx. 18%E
5	*Meat lean, ham leaner, fish, eggs* Food group with high-quality protein for metabolism and muscle supply. In addition, suppliers of B vitamins, iron, and zinc Lean meat is preferable The consumption of sea fish (salmon, mackerel, tuna) also provides long-chain unsaturated fatty acids (omega-3 fatty acids, o-3FAc) Every week 2–3 portions of meat and fish (100–200 g depending on energy and protein requirements), eggs	Approx. 7%E

(continued)

Table 18.3 (continued)

Circle group	Foods	Part of energy intake
6	*Oils and fats* Fats should be restricted as an energy-rich nutrient group, and vegetable oils should be preferred because they contain essential unsaturated fatty acids (USFAc), vitamin E, secondary plant substances (prebiotics) Spreadable fat is not necessary, but if desired, then high-quality margarine should be used In ready-to-eat foods from the trade, care should be taken to ensure that the fat (max. 1.5 g/100 g) and salt content is low For salads use the high-quality oils (from rapeseed, olive, soybean, linseed, pumpkin seed) and for frying, coconut oil or palm oil, which are better for this purpose! It should not be consumed and ends up in the waste	Approx. 2%e
7	*Drinks* They are designed to quench thirst (water!) and are indispensable for performance. The daily fluid requirement of 1.5–3 l/d should be covered mainly with water and hardly contribute to the energy intake.The supply of nutrients from fruit juices, lemonades, or the like is insignificant, as these, if not pressed themselves, are only sweetened.A look at the list of ingredients is necessary	

Graphically displayed recommendations for food selection are presented in the DGE nutrition circle (► www.dge.de/gesunde-ernaehrung/dge-ernaehrungsempfehlungen/dge-ernaehrungskreis/) and in the three-dimensional DGE food pyramid (► www.dge.de/gesunde-ernaehrung/dge-ernaehrungsempfehlungen/dreidimensionale-dge-lebensmittelpyramide/)

18.9 Safe Nutrition at Altitude to Prevent Nutrient Deficiencies and Dehydration

There is a lack of precise, scientifically sound guidelines for nutrition in the high mountains that are based on basic needs and actual needs. According to the usual training-dominant diet, a special, individually adapted plan must be created for the altitude. The usual eating behaviour during mountain activities (including preferred foods, supplements, liquids, frequency of consumption of food groups in the mountains, appetite) must be adapted to the conditions during staying at high altitude.

The DGE nutrition circle shows, at one glance, what a healthy and ecologically sustainable diet looks like. It is a kind of guide giving optimal food selection examples. The size of the food group sector illustrates the necessary proportion of the diet. The larger a food group, the more can be eaten. It is recommended to use a variety of foods within the groups and to eat a very varied diet with different groups.

A healthy and environmentally friendly diet is more than 3/4 plant-based and just under 1/4 animal-based (see sum of the percentages in Table 18.3).

(► https://www.dge.de/gesunde-ernaehrung/dge-ernaehrungsempfehlungen/dge-ernaehrungskreis/)

18.9.1 Activity-Related Need for Carbohydrates

Carbohydrates (CH, polysaccharides) from food are the main source of energy for energy supply during intense physical activity and at high altitudes and are optimal for energy supply per litre of oxygen consumption. Ideally, they should be available 2–3 h before the start of the training/tour, during the tour with intensive physical activity in several small portions and immediately after the end of the tour for recovery and replenishment of glycogen stores in the liver and muscles.

Glycogen stores in the muscles and liver are available for an aerobic exercise of about 60–90 min. After that, snacks on the mountain with long-chain carbohydrates (CH, polysaccharides, maltodextrin) are necessary for the current energy supply.

Abundant consumption of CH during intensive exercise under hypoxia can alleviate negative symptoms of high altitude. At altitude, the need of carbohydrates is greater than at sea level.

According to the DACH guidelines, the CH share of 50–60% daily energy need amounts to 1250–1500 kcal or 313–37 g for 2500 kcal or 4.5–5.4 g/kgd for 70 kg body weight! This covers the daily requirement during low physical exertion. For a higher load, especially during walking in the high mountains, more CH are necessary to protect performance (◘ Table 18.4).

In preparation for several hours (>3 h) of high-intensity or very high-intensity physical activity, it is important to safely fill the hepatic and muscular glycogen stores before start. The level of glycogen stores correlates closely with the possible duration of exposure. In the 2–3 days before the planned tour, "carbohydrate loading" with an increased intake of carbohydrates in the diet plan is recommended to achieve full glycogen stores. This requires 10–12gCH/kg on at least 2 days or longer before the start of the tour (◘ Table 18.4).

The usual muscle glycogen content can be increased by about 15%. Likewise, 2–3 h before the start of the activity in the morning, the nightly breakdown of carbohydrates and glycogen before the start of the activity should be compensated for by a carbohydrate-rich breakfast. Undersupply can contribute to central fatigue.

At the same time, it is necessary to reduce fatty foods containing saturated fatty acids. The course of the nutrition plan for the high mountain tour should be tested beforehand to ensure tolerance.

On the day of the tour, it makes sense to supply carbohydrates in quantities according to the intensity of the load with several small meals in an interval of about 90 min in

◘ **Table 18.4** Recommended carbohydrate (CH) intake depending on different exercise intensities (Thomas et al. 2016)

Physical strain	**Recommended CH intake (g/kg day)**	**CH fraction 70 kg BW (Intake g)**	**CH-energy kcal (%E of 2800 kcal/d)**
Low intensity	3–5 g/kg day	(5) 350 g	1400 kcal/50%
Moderate intensity	5–7 g/kg day	(7) 490 g	1960 kcal/70%
High intensity(1–3 h/day)	6–10 g/kg day	(8) 560 g	2240 kcal/90%
Very high intensity(4–5 h/day)	8–12 g/kg day	(10) 700 g	2800 kcal/100%

order to avoid a stressful, too high, gastrointestinal filling. On the one hand, this reduces the energy supply at altitude, with the lower oxygen supply due to the less efficient fatty acid oxidation per litre of O_2.

On the other hand, this physiological regulation could also be used during prolonged exertion to achieve the reduction of body fat through energy consumption and to prevent logistically complex care of carbohydrates. Less performance due to lower O_2 efficiency must be accepted. However, with a good logistical supply of CH for a longer duration of exercise, the risk of stress interruption due to hypoglycaemia is reduced with a high CH energy rate. The possible loss of muscle mass is also restricted.

For mountain tours over 3 h with high load, an estimated 90 g carbohydrates (CH)/h are consumed. The amount can be absorbed with CH beverages at a concentration of 60 g CH/l and gastrointestinal tolerance with a drinking volume of 1.5 l/h. Since the large amount of water is problematic on a mountain tour, food must be available for the supply of carbohydrates. Wholesome 100 g wholemeal rye bread would already provide 38gCH. A portion of muesli (50 g) has about 30 g of carbohydrates and a simple muesli bar (25 g) has an average of 11 g CH. Such "power bars" have very different CH proportions ranging from 30 to 70 g/100 g (approx. 2–3 pieces). These can be found on the packet's nutrition list. With one meal of vegetable risotto (250 g), you can absorb 38gCH.

For a 5-h mountain tour with high load, about 450gCH would be necessary! The logistical supply of this essential energy supplier must therefore be planned and tested before the tour (Wahrburg and Egert 2017).

However, because the CH requirement is increased during stays at high altitudes under intensive stress, it cannot be assumed that the greatly increased intake will increase performance. After several weeks of stay and adaptation to hypoxia in the base camp, a very high CH intake above the normal requirement does not cause an increase in performance but does ensure best performance.

> Only cover the estimated demand with CH food! All days and at altitude!

18.9.1.1 Protein for the Maintenance of Lean Body Mass (LBW)

Weight loss and decrease in lean body mass (about 60% of weight loss) are a consequence of hypobaric hypoxia in mountaineering, especially at high altitude (>5000 m) (Wing-Gaia 2014). Down regulation of protein synthesis and protein breakdown in the muscle with empty glycogen stores or an insufficient supply of energy and protein can be the cause. Safe protein nutrition during prolonged stays at altitude is therefore necessary to maintain performance. This must be well planned and adhered to, as satiety is higher at altitude due to a protein-rich diet. There are no general guidelines for the necessary daily protein dose in connection with intensive physical activity in competitive sports. Low intake with a negative nitrogen balance leads to protein catabolism and low regeneration in the base camp after a demanding high mountain tour.

For a wholesome diet for adults, the DACH reference values recommend about 0.8 g/kg LBW (lean body weight) protein intake or 1 g/kg LBW for older people. According to scientific studies in endurance and competitive athletes, the requirement is 1.2–1.7 g/kg LBW. A meta-regression from 49 studies resulted in a necessary intake of 1.62 g/kgd. A higher amount no longer leads to an increase in lean body mass. At 70 kg body weight, this would correspond to a protein amount of at least 115 g/d, which would be present in about 500 g roast beef (four portions of 125 g each, pork chop, chicken breast), in about 600 g trout (four portions of 150 g each, salmon). Mountain cheese with 45% dry matter can provide the same amounts of protein. If this calculated intake is too high, protein supplements can support the supply. However, whey powder, for example, only provides 11 g of protein in 100 g, but skimmed milk powder provides 36 g/100 g and egg powder 46 g/100 g! Processed together with rice, potatoes, soy or similar, these can contribute to a full-fledged supply due to their higher biological value (▣ Table 18.5). If protein supplements are used, then select those with 1000–3000 mg leucine (Coffey et al. 2011; DGE 2015; Morton et al. 2018).

Due to the different biological value of protein (BV) from different foods, optimal combinations of animal and plant sources should be consumed to meet the need for essential amino acids with a low consumption quantity. The biological value of food proteins is the measure of the efficiency with which they can be converted into the body's own proteins. For example, whey protein (BV 104) and whole egg (BV 100) have the highest values, while oatmeal (BV 60) or lentils (BV 60) have low values, and this shows animal protein has high and vegetable protein low BVs. However, the supply of essential amino acids and thus the BV becomes significantly higher when plant and animal foods are mixed. With milk (75%) and wheat flour (25%), a BV of 125 is obtained (▣ Table 18.5).

If a protein-rich supply of food is not feasible on the tour at altitude, then powder mixtures or protein bars should be used as dietary supplements, with a high protein content (>20 g/100 g) and with a high BV (e.g. whey protein with egg, or soy, potato). Protein supplements high in branched-chain amino acids, especially leucine, can improve muscle protein synthesis and stabilise lean body mass (24 g whey protein, 4.8 g leucine, and 50 g maltodextrin) (Coffey et al. 2011). In the normal daily diet, the combinations of plant and animal foods are more favourable for protein supply, and protein supplements are only necessary if there are risks of

▣ **Table 18.5** Biological value (BV) of food protein

Food (ac. Kofranyi und Wirths 1994)	(BV)
Whole egg	100
Tuna	92
Egg white	88
Pork, Edam cheese	85
Beef, soy	84
Brown rice	83
Cow's milk, quinoa	82
Low-fat curd cheese	82
Poultry, rye flour	80
Potato	76
Fish (trout, cod, salmon)	75
Maize	74
Soybeans	72
Oats, lenses	60
Peas, wheat flour	59
Hazelnut	50
Carrots	36
34% whole egg +66% potatoes	136
70% whey protein + potatoes	134
75% milk +25% wheat flour	125
60% whole egg +40% soy	123
75% whole egg +25% milk	121
68% whole egg +32% wheat flour	120
55% whole egg +45% peas	120
88% whole egg +12% maize	114
51% milk +49% potatoes	114
77% beef +23% potatoes	113
55% soy +45% rice	111
75% milk +25% wheat	105
45% soy +55% potatoes	103
51% beans +49% maize	99

insufficient coverage of needs (loss of appetite, weight loss diets, intolerances, one-sided and vegan diets).

18.9.1.2 Supply of Dietary Protein During the Tour Preparation and During the Stay at Altitude

If training with endurance load training for muscular development is intended for mountain tours, then a higher protein intake is expedient. For tours lasting several weeks at high altitudes, the requirement must be met with an adapted body mass of 1.3 g/kg LBW, but a higher amount of 1.7 g/kg LBW is necessary in the case of low energy intake (loss of appetite, logistics) to reduce the loss of lean body mass (LBM).

If intensive physical exertion, with about 4500 kcal/d energy consumption, is going to be carried out, then a protein intake of about 120 g/d would be necessary for 70 kg body weight, which is about 11% of E. For this amount about 600 g of lean beef or 500 g of lean cheese (<40% fat in dry mass; FDM) needs to be eaten. In extreme mountaineering, such amounts of protein are therefore only possible with low-volume supplements rich in leucine and are necessary for stays of several weeks.

This high protein requirement together with high carbohydrate intake can increase protein synthesis. However, an iso-caloric exchange of carbohydrates with protein does not improve performance. In addition, a sufficient energy intake is necessary; otherwise, body and food protein serve as energy suppliers. From a metabolic point of view, it is important to ensure that the necessary high energy and nutrient intake is well distributed throughout the day by frequent consumption, adapted to the planned activity with the aim of achieving a continuous supply, and mirrors the anticipated consumption on the tour to the altitude and during recovery at the base camp! What has been absorbed and consumed must be supplied later! The practical individual planning includes a meal 3 h before the tour and small meal breaks with protein and CH snacks every 2–3 h during the tour, as well as early meals for recovery afterwards in the base camp! A nutrition plan is also intended to remedy the loss of appetite at altitude and to ensure a whole food diet. A proper nutrition plan stabilises muscle mass! Don't eat according to appetite, but according to the plan! If the energy supply is not sufficient, then the protein intake should be increased.

18.9.1.3 Which Proportion Should Fats Be in the Diet of Endurance Athletes?

Compared to carbohydrate or protein intake, fats on the mountain play a rather subordinate role in the diet. In connection with expected physical exertion, training or tours at altitude, the fat content in the daily diet plan must change. To maintain the energy balance, high-quality fat consumption is important for regeneration in the camp, for replenishing intramuscular triglyceride stores and for the absorption of essential fatty acids and fat-soluble nutrients. Foods with valuable fats, polyunsaturated fatty acids, and fat-soluble vitamins (A, D, E, K) are vital and therefore also important for endurance athletes, high-altitude mountaineers with longer stays at altitude. Without dietary fats, the body would not be able to use these vitamins properly.

If appropriate quality foods are not available, the regular consumption of appropriate dietary supplements (polyunsaturated fatty acids and vitamins) is necessary (DGE 2015). These cheap fats are also carriers of flavours and aromas.

To control dietary fat intake in one's diet plan, it is helpful to study a nutritional table for better food choices and to cooperate or train with an alpine or competitive sports nutrition specialist. Various studies of the dietary habits of competitive athletes (pentathlon, triathlon, Ironman, CrossFit) showed that they consume 28–40% fat with energy intake of 2500 kcal/d to 3700 kcal/d (Schek et al. 2019).

For the diet of alpine athletes at altitude, such eating habits are not performance-enhancing. In endurance sports, gastrointestinal complaints with a high-fat diet have also been observed (Schek et al. 2019). Therefore, the restriction of fat intake, especially of unsaturated or trans fatty acids, should have already been planned in the preparation camp at lower altitudes.

Some foods are intended to give examples of fat supply (◘ Table 18.6). For a lower consumption of dietary fat, 0.5–1 g/kgd is recommended, which corresponds to a maximum of 70 g/d or 630 kcal/d at 70 kg body weight. For about 1800 kcal/d RE and a high level of physical activity with PAL = 2.5, this would be 17.5%E for dietary fat and 16% of E with the meals selected in ◘ Table 18.6.

With the meals spread over the day, a high-quality protein supply can also be achieved. A protein intake of 62 g/d is achieved, which corresponds to 0.88 g/kgd at 70 kg body weight and 5% of E.

According to the DACH guideline, the fat intake should not exceed 30% of E and not fall below 20% of E. A low-fat diet at altitude, with plenty of CH and protein, optimises the respiratory quotient, increases the oxygen partial pressure, and improves the arterial oxygen supply. For this reason, athletes are also recommended to consume a moderate amount of fat (approx. 20% of E) during altitude training, but this results in a slightly higher volume of food, which requires more planning. To control dietary fat intake, energy and nutritional tables are helpful, allowing you to control the desired diet plan and choose wholesome alternatives (e.g. Wahrburg and Egert 2017, ► www.trias-gesundheit.de).

With a wholesome diet and fat intake of up to 30% of E, different fatty acid fractions should be strived for, which correspond to a fat content of 99 g/d at 3000 kcal/d and a breakdown of about 33 g per fat group (DGE guidelines):

- <10% of E saturated fatty acids (max. One third of the fat energy consumed).
- 7–10% of E polyunsaturated fatty acids (PUFA, sum of omega-3 and omega-6 fatty acids) or 10% of E if saturated fatty

◘ **Table 18.6** Fat consumption with food (0.51 g/kg d; KG 70 kg, EU 4800 kcal/d)

RE 1800 kcal/d ×PAL 2.5	Portion (P) (g)	Fat (g)	Energy (kcal/P)	%E 4800 (kcal/d)	Protein (g)
Yoghurt	150	6	100	1.1	5
Wholemeal rye bread	200	2	372	0.4	12
Margarine, spreadable fat	40	32	288	6.1	0
Sheep's milk	250	14	242	2.7	18
Vegetable risotto	250	10	262	1.9	5
Lamb chop	125	21	286	4.0	22
Sum	1015	85	1550	16.1	62

RE resting energy
Wahrburg und Egert (2017)

acids exceed (SFA) 10% of E of the total energy intake.
- Monounsaturated fatty acids (MUFA) cover the difference to the total fat content.
- Trans fatty acids (TFAc) should be avoided! A maximum of <1%E.

In contrast to other unsaturated fatty acids (USFA), trans fatty acids (TFA) are suspected of having harmful properties on the organism. These are not acceptable for a wholesome diet. If the consumption of trans fatty acids increases >1%E, the risk of coronary heart disease increases more than tenfold (Schek et al. 2019). These fatty acids, which should be avoided, are mainly produced during heating and industrial processing, while they are found in frying oil, margarine, nut nougat cream, potato chips or fries and in instant soups during industrial hardening of fats. In fried foods, up to 34% of the fats are trans fatty acids.

> When consuming trans fatty acids, LDL cholesterol increases, and HDL cholesterol decreases. Therefore, for example, frying fats from the pan should only end up in the trash. Use high-quality oils only moderately heated (<60 °C)! They are used in flavourings and in salads and vegetables for whole food nutrition and promote the absorption of fat-soluble nutrients from plant foods.

Sources of monounsaturated fatty acids are: olive oil, hazelnuts, peanut oil, rapeseed oil. Essential polyunsaturated fatty acids (PUFA), linoleic acid (omega-6), alpha-linolenic acid (omega-3), eicosapentaenoic acid (EPA, omega-3), and docosahexaenoic acid (DHA, omega-3) are found in high-quality oils (linseed oil, walnut oil, rapeseed oil, soybean oil, pumpkin seed oil), marine fish (tuna, salmon, mackerel), and nuts, sunflower and pumpkin seeds (examples in Table 18.7).

Even with the lower limit of 20% of E fat in the wholesome diet, it must be ensured that sufficient essential fatty acids and fat-soluble vitamins are absorbed, a feeling of satiety is achieved, and intramuscular triglycerides are replenished after long exercise to maintain performance. When staying at altitude for a longer period, the "reduced" fat intake must be so high that the vital ingredients (vitamins, fatty acids) are avail-

Table 18.7 Examples for fatty acid in foods

	Energy kcal/110g	Fat g/100 g	Simple USFA g/100	MUSFA g/100 g	Fat part %fat
Roast beef	131	4	2	Less	50.0
Beef liver	131	4	1	1	25.0
Tuna	144	5	2	1	40.0
Mackerel	182	12	5	3	41.7
Avocado	217	24	17	2	70.8
Peanuts	564	48	22	14	45.8
Pumpkin seeds	560	46	11	24	23.9
Sunflower seeds	575	49	11	30	22.4
Walnuts	654	63	10	43	15.9

able. If this is not possible for logistical or volume reasons, supplements are required when staying at altitude for more than a week. In the usual diet of amateur athletes (pentathlon, triathlon, fitness sports), the fat content of 31–39.6% of E was always found above the recommended 30% of E.

In a whole-food diet with low fat, the fatty acids that meet the requirements are necessary for the various important metabolic influences. The intake of essential fatty acids recommended by the DGE, which cannot be formed in the human body, amounts to 2.5% of E for linoleic acid (omega-6) and 0.5% of E for α-linolenic acid (omega-3) for adolescents and adults.

With a high energy requirement on the mountain of 4500 kcal/d, 12.5 g/d linoleic acid and 2.5 g/d linolenic acid would be desirable according to this recommendation. This can be achieved with 100 g nuts, pumpkin seed, or sunflower oil, 200 g salmon, 250 g mackerel or supplementally with omega-3 sea fish oil capsules (see nutritional table). Dosages of approximately 5 g/d were observed without side effects (EFSA 2013).

Fresh sea fish on the mountain is certainly a logistical problem. But it can be replaced by canned tuna (8.5 g/100 g USFA; 24 g/100 g protein), sprats (7.5 g/100 g USFA; 8.5 g/100 g protein), 200 g herring tip or smoked salmon to cover the essential fatty acid requirement. Canned meat is also an acceptable alternative (e.g. chicken in rapeseed oil; 17 g/100 g MUFA; 17 g/100 g protein). This depends on the preservation in the rapeseed oil, which must then also be consumed. In the EU, the ingredients on packaged foods are mandatory and thus support nutrition planning.

Saturated fatty acids dominate in animal foods. They are found in abundance in beef, beef fat (tallow), lamb, pork, poultry with skin, sausages, bacon, lard, cream, butter, and cheese. SFA are also in vegetable foods (coconut fat, palm oil, palm kernel oil) as well as in baked and fried foods. Ready-made products with a high proportion should be avoided.

Marine fish and plant foods with monounsaturated and polyunsaturated fatty acids in the whole food diet are important for their beneficial metabolic influence. The amount of saturated fatty acids present can be found on the labels of packaged foods or oils. Valuable oils (rapeseed oil, olive oil, corn germ oil, pumpkin seed oil, sunflower oil, linseed oil, walnut oil) should not be heated to high temperatures for consumption (e.g. roasting) because ingredients are destroyed and even trans fatty acids are formed, which are risky to health in the long term. The frying fat from the pan belongs in the trash! Butter or margarine as a spread is also not necessary and rejecting it promotes the saving of fat. Plan milk and yoghurt with max. 1.5% DMF!

Attempts to improve endurance performance and conserve glycogen reserves with fat intake have shown that fatty acid oxidation increases but does not improve performance. Dietary supplements with fatty acids also do not show any performance-enhancing effects, although the supply of essential fatty acids and fat-soluble vitamins is necessary, especially in the case of a prolonged low-fat diet at altitude. In addition to the vital polyunsaturated fatty acids (linoleic acid, linolenic acid, EPA, DHA), high-quality oils contain substances that have a positive effect on the metabolism. Therefore, high-quality oil consumption is also important for a low-fat diet.

Pumpkin seed oil has one of the highest concentrations of monounsaturated and polyunsaturated fatty acids at 80%. With one tablespoon (approx. 10 g), 8 g of PUFA can be absorbed and thus cover the requirement significantly. It also contains minerals (K, Mg, Ca, P, Cu, Se, Zn, Mn, J, F) and vitamins (A, B1, B2, B6, C, D, E), numerous phytosterols, and plant sterols. With the high vitamin E content (average 29 mg/100 g), one serving of Styrian pumpkin seed oil

(1tbsp, 10 ml) can cover up to 20% of our daily nutritional needs, and it tastes pleasant straight from the spoon.

Accompanying substances in the high-quality oils support the metabolism, show an antioxidant effect and higher arterial oxygen saturation (e.g. vitamin C, α-tocopherol, and α-lipoic acid) during intense physical exertion, kill parasites in our body (cocurbitasterols; ► http://www.omega-oele.de/kurbiskernoele-und-die-gesundheit/), promote the immune system, and reduce AMS risk at high altitudes. The daily intake of vegetable oils is to be ensured in the nutritional program for the altitude. While polyphenols, fibre, glutamine, vitamins A and D, among others, strengthen the barrier function, emulsifiers in foods (sauces, mayonnaise), non-steroidal anti-inflammatory drugs (NSAIDs), alcohol, larger amounts of separate fructose, a diet high in fat and sugar or bacterial lipopolysaccharides (LPS) can weaken the intestinal barrier.

18.9.2 Dietary Fats and Their Influence on the Immune System

The Western-influenced diet with a dominant consumption of meat, saturated fatty acids, sugar-rich drinks, intensively industrially processed foods, leads to an unfavourable intestinal flora and damage to the intestinal barrier, which is accompanied by a low-grade inflammation in the body (endotoxinaemia, slightly increased CRP). For a longer stay at altitude, preventive care for the immune system must not be neglected.

A Mediterranean diet, with a high proportion of diverse vegetables and fruit combined with high-quality cooking oil (olive oil, rapeseed oil, pumpkin seed oil), has a beneficial effect on the intestinal flora and the intestinal barrier. Furthermore, abundantly consumed legumes, seeds and nuts, onions, garlic, and herbs contribute to the promotion of the intestinal microbiome.

The gut-associated immune system responds primarily to the omega-6 and omega-3 fatty acids contained in these foods, polyphenols together with fermentable, soluble, and insoluble dietary fibres (pectin, inulin, beta-glucans, FOS, GOS, resistant starch), vitamins A and D, trace elements (Zn, Fe, Sn) with positive effects.

> Important foods for the microbiota supply of fermentable fibre are apples, carrots, asparagus, parsnips, chicory, onions, wholemeal flours (breads), mushrooms and legumes (◘ Table 18.8).

Acute altitude sickness (AMS) could be mediated by damage to the blood-brain barrier by free radicals. Enteral antioxidant vitamin supplements about 2–3 weeks before, during ascent, and during stay at high altitudes could contribute to the reduction of AMS risk. A dosage of 250 mg L-ascorbic acid, 100 IU dl-α-tocopherol acetate, and 150 mg α-lipoic acid in the morning after breakfast and after dinner can reduce the frequency of specific altitude symptoms (headache, gastrointestinal problems, dizziness, fatigue, sleep disturbances) by half. The physiological profile of mountaineers was observed with arterial oxygen saturation and adjusted energy uptake at altitude. With an increased iron (20–40 mg/d) and vitamin D supply (2000–4000 IU/d), a promotion of erythropoiesis has been observed. This improves the oxygen supply during physical exertion at altitude and decreasing oxygen concentration in the air.

Table 18.8 Examples of optimising nutrition—promoting a "healthy" microbiota with protein, fatty acids, fibre content in food

	Protein (g/100 g)	Unsaturated fatty acids (g/100 g)	Polyunsaturated fatty acids (g/100 g)	Fibre (g/100 g)	Na (mg/100 g)
Wholemeal spelt flour	14.4	0.43	1.17	8.38	–
Oatmeal	13.5	2.7	2.64	10.0	7
Rye flour type 1800	10.8			13.9	2
Wholemeal Rye bread	7.3			8.1	527
Wheat flour type 1700	12.1			11.7	2
Wholemeal wheat bread	7.5			7.4	448
White beans	21.1			23.2	3.5
Pea pod green	6.55	0.04	0.3	4.25	2.0
Pea seeds dry	22.9	0.11	0.79	16.6	26
Poppy seeds dry	23.8	4.47	31.12	20.5	21
Soybean dry	37.6	4.09	10.73	22.0	4.7
Sunflower	26.5	13.5	28.0	6.3	2
Cauliflower	2.46	+	0.13	2.92	16
Chicory	1.27	+	0.1	1.26	4
Kale	4.3	0.02	0.48	4.2	42
Dandelion leaves	2.87	0.01	0.37	3.02	76
Leek	2.21	0.01	0.17	2.27	4.4
Brussels sprouts	4.45	0.01	0.19	4.4	9.2
Red cabbage	1.5	+	0.1	2.5	11
Asparagus	1.91	0.01	0.08	1.31	4,1
White cabbage	1.37	+	0.11	2.96	12
Carrot, carrot	0.98	0.04	0.12	3.63	61
Beetroot/ beetroot	1.53	0.01	0.05	2.53	58

(continued)

Table 18.8 (continued)

	Protein (g/100 g)	Unsaturated fatty acids (g/100 g)	Polyunsaturated fatty acids (g/100 g)	Fibre (g/100 g)	Na (mg/100 g)
Celery	1.55	0.01	0.17	4.23	77
Onion	1.18	0.1	0.01	1.81	3.0
Green beans	2.39	0.01	0.11	1.89	1.5
Cucumber	0.6	0.01	0.09	0.54	3.0
Pepper	1.08	0.01	0.13	3.59	1.5
Sorrel leaf	3.19	0.12	0.19	1.95	–
Tomato	0.95	0.03	0.1	0.95	3.3
Oyster mushroom	3.46	0.02	0.1	5.85	6.0
Mushroom	4.11		0.15	2.03	7.9
Peanut roasted	30.2	22.7	14.8	11.4	5.7
Hazelnut	14.1	46.0	8.6	8.2	2.0
Walnut	17.0	10.9	41.7	6.14	2.4
Pumpkin seeds	24.0	10.6	23,6	8.8	18
Pineapple	0.46	0.02	0.08	0.99	2.1
Orange	1.0	+	+	1.6	1.4
Raspberry	1.3	0.03	0.19	4.68	1.3
Plum	0.6	0.05	0.08	1.58	1.7
Apple	0.34	0.02	0.24	2.02	1.2
Sour cherry	0.9	0.13	0.15	1.04	2.0

Fröleke (2006)

18.9.3 Fats, Fibre, Probiotics to Promote the Intestinal Flora and the Immune System

Health effects by the nutritive promotion of the intestinal flora can be achieved through a long-term comprehensive modification of the diet and with an optimal supply, which reaches a weekly average of 35 g/d (Fröleke "Small Nutritional Table" DGE; Table 18.8). If, as on high mountain tours lasting several weeks, a fibre supply with fresh food is not possible, then supplements with a fibre mixture are necessary for intestinal care or muesli mixtures with the appropriate fibre content. Within a week, at least half of the average daily intake should be safely consumed with an adequate daily water supply.

Supplements with mixtures of fibre, minerals, vitamins, and bacterial strains are offered in abundance on the Internet. In the case of bacterial supplements, several strains should be present in high concentrations ($\geq 10^{10}$ germs/portion) (various Lactobacilli, Bifidobacteria, Enterococcus faecium, Lactococcus, Saccharomyces, Akkermansia, Faecalibacterium, Roseburia) combined with carbohydrates (oligosaccharides, polysaccharides, FOS, prebiotics), potassium, magnesium, enzymes (amylases). These probiotic bacteria compete with other gut bacteria for nutrients, and their metabolites inhibit the growth of pathogenic bacteria.

› A plant-based diet with plentiful, low-processed foods has a positive effect on the gut microbiota, which are beneficial for health.

18.9.4 Optimal Fluid Balance at Altitude

Hypoxia at high altitude, high respiratory rate due to low O_2 partial pressure in the air we breathe, intense activity and low humidity increase fluid loss and contribute to dehydration, which reduces aerobic capacity and thus performance at high altitudes. Reduced thirst feeling at high altitudes changes drinking habits and is another dehydration factor. In addition, the water supply is limited when more dried and less fresh foods (dairy products, eggs, fruits, vegetables) are consumed, which is predominantly (80–90%) the case (Karpęcka-Gałka et al. 2023a, b).

Weight loss at altitude above 2–4% BW due to sweat and breath loss reduces performance and increases the need for water, due to physical activity, climatic conditions, body weight, clothing, and training condition. In the cold, increased diuresis can occur (altitude diuresis), which affects the blood concentration. Reduced cerebral blood flow in severe dehydration results in AMS symptoms and these impair physical performances. In the case of exertion that lasts longer than an hour, it is necessary to drink during the activity. At moderate altitudes up to 4000 m, the loss of breathing water can increase to about 2 l/d and increase by 0.5 l/d due to urine excretion. Surveys of mountaineers show that almost half of respondents in the mountains consume 2–3 l of fluids per day, while about the same proportion drink smaller amounts per day, which can lead to dehydration and have a negative impact on acclimatisation (Karpęcka-Gałka et al. 2023a, b).

According to ACSM (American College of Sports Medicine) experts, the daily fluid requirement during intense physical activity is 4–5 l/d. Individual monitoring of fluid status through logging and standardised weighing at base camp is important to determine the fluid needs of mountaineers. The fluid requirement depends on the normal metabolism (35 ml/kgd) and the individual sweat rate (weight loss), which can vary greatly between and within individuals. In case of severe dehydration and low regeneration time (<12 h), a stricter rehydration plan should be implemented. For quick complete rehydration, about 1.5 l of fluid per kg of weight loss is recommended.

It is an important goal to drink enough to keep your body weight constant. The nutrition plan is intended to fulfil a fractional drinking plan. On the evening before the planned tour, 0.5 l water or CH drink, the same in the morning when waking up and again half an hour before the start. During the ascent, 0.25 l of water or CH drink every quarter of an hour. Under no circumstances should you rely only on the feeling of thirst. This is reduced in intensity and only occurs significantly when you have already lost a lot of sweat and thus body weight. After the day's tour in the camp, drink the weight difference at least with electrolyte supplementation (especially Na). After adapting at altitude, in the base camp, it can be expected that fluid losses will decrease. Especially in the first days of acclimatisation at altitude, regular monitoring of weight (in the morning, fasting, after the toilet), body mass, and drinking quantities will ensure performance and reduce the health risk.

18.9.5 Suitable Drinks for Rehydration

The mineral supply must also be determined with the necessary drinking quantities. The mineral content of sweat is very variable. The priority is to consider its sodium content, which is on average around 900 mg/l and must be replaced with drinks. With a sweat loss of 4% and a body weight of 70 kg, 2.52 g of Na is lost. Together with a normal daily Na requirement of 8 g/d, 10–11 g/d of Na would be ingested with food and beverages during heavy physical exertion. On the other hand, fresh meat provides approx. 50–120 mg/100 g, meat and sausage products 500–2500 mg/100 g (smoked meat 2472 mg/100 g), canned fish 1–2.5 g/100 g, and the important microbiome vegetables (◘ Table 18.8) only 13.4 mg/100 g on average. Under the tour conditions at altitude, it is not possible to cover the need for Na, other minerals, and vitamins with the normal diet. Thus, Na, Fe, K, and Mg (to compensate for losses) as well as vitamins C, E, and D (for the increased requirement and risk reduction) needs to be covered daily by using supplements.

Low-mineral beverages (tap water, low-sodium mineral water) without carbohydrates (maltodextrin, oligosaccharides, inulin) can lead to hyponatraemia (plasma sodium content <135 mmol/l). On the mountain, if more low-sodium fluid is absorbed than sodium is excreted through sweat and urine during high exertion, Na homeostasis can become disordered. Since the water and electrolyte balance are closely related to each other both during absorption in the intestine and in the metabolism, the composition of the drink also plays a role in water absorption.

The optimal drink should provide water, minerals, and carbohydrates (CH) as quickly as possible during long (>90 min) and high physical exertion tours on the mountain. This helps to delay fatigue and replace sodium losses. The best water absorption is achieved via slightly hypotonic or isotonic beverages with a CH concentration of 4–8 g/100 ml and 400–1100 mg/l sodium. With this drink composition, rapid stomach passage and absorption of the fluid in the intestine can be achieved.

The supply of other minerals or vitamins is not necessary during exertion on the mountain if the previous supply is good but is necessary for recovery in the camp (◘ Table 18.9). If other electrolytes are added to the sports drink, they should not significantly exceed the upper limits of approx. 225 mg/l K and ca. 100 mg/l Mg. Not only during exertion, but also during the regeneration phase in the base camp, the sodium content in the drink should be assured to counteract diuresis. For example, broth (vegetable broth 495 mg/100 g, chicken broth 248 mg/100 g), sodium-rich sports drinks or soups (beef soup 333 mg/100 g) are suitable drinks. Fruit juice spritzers, made from fruit juice and sodium-rich, low-carbonated mineral water (diluting juice

◘ **Table 18.9** Recommendations for nutrient content in an isotonic rehydration drink

KH (g/l)	Na (mg/l)	Cl (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Osmolarity (mmol/kg)
60–80	400–1100	400–1500	120–225	45–225	10–100	<300

Brouns et al. (1992)

with water 1:2), are also suitable for rehydration.

In 2–4 h before exercise, a balanced fluid balance should be achieved with 5–10 ml/kg body weight; the urine colour should be light yellow. This corresponds to about 350–700 ml at 70 kg body weight. Excessive fluid intake without Na can put you at risk of hyponatraemia. Before the mountain tour, start with normal plasma electrolyte concentrations, after a good recovery the day before. Drink enough fluids during the day and do not skip meals, as these support the supply through the content of water and osmotically active components, such as sodium.

Within the first days of acclimatisation at altitude, regular monitoring of weight, body mass, and the amount of drinking fluid will ensure performance and reduce the health risk. Weighing the body in the morning before and immediately after exertion to determine the individual fluid loss under load provides orientation for the optimal amount of fluid to drink under exertion. If the body weight is reduced by less than 5% and there is no need for renewed exercise in the next 24 h, athletes can replace fluids (2–3 l/d fluid and food) and electrolytes as desired. The consumption of normal main meals and snacks combined with enough water ensures the restoration of fluid and electrolyte balance. To avoid diuresis, water should be supplied in small sips over a longer period, together with the necessary electrolytes, in conjunction with a (snack) meal to enable optimal rehydration. For optimal care, it is recommended to organise a drinking plan divided into several small quantities, both on the tour and on the day of recovery.

18.9.6 Physical Performance Related to Minerals

After exertion, glycogen stores must also be replenished. Sufficient potassium is necessary for this (e.g. in fruit juices and dried fruit), because potassium is necessary to store carbohydrates in the body. Each gram of glycogen requires 19 mg of potassium and about 3 g of water. Drinking low-fat milk (≤1.5% fat) with a high content of protein, Na, K, Ca, Mg, and P is said to have caused a positive fluid balance and satiety after loss of lean body mass. Skimmed milk or whey powder mixed with water (10 g/100 ml, 35 kcal, Na 80 mg, K 220 mg, Ca 150 mg, Mg 12 mg) with the possible addition of dark chocolate (as cocoa) would therefore be a logistically favourable alternative for supply at altitude.

Industrially, “hypotonic”, “isotonic”, and “hypertonic” drinks are offered:

- *Hypotonic* exercises are suitable for short (<1 h) high-intensity loads with optimal fluid intake but limited energy supply.
- *Isotonic* are carbohydrate sources with electrolytes that are lost during sweating. They are suitable for intensive activities with longer durations.
- *Hypertonic* provide a very high carbohydrate content (>8%). Their absorption rate is slower, but they offer a direct supply of energy and a quick way to replenish glycogen stores soon (<1 h) after exercise, making them better than solid food. At the same time, they offer optimal amounts of minerals and vitamins as well as a protein content with essential amino acids, which prevents body mass loss during heavy exertion. For endurance exercise at altitude, this is the optimal mixture during the tour and for regeneration afterwards.

In the tour drink, an optimal individual mixture with the water on the mountain can be prepared with the powders offered. Hypertonic solution is suitable for high-intensity long workouts (>2 h) and for workouts where the sweat rate is slightly lower. Before the tour, check the drinks for tolerance!

With the average diet in the population, an undersupply to the degree of malnutrition in athletes has been repeatedly reported. The usual DACH reference values consider the usual lifestyle in our region but are not adapted to special demands due to above-average physical exertion during sports or at altitude. To do this, the DACH average values must be modified. There are few scientifically sufficiently proven consumption recommendations for minerals or vitamins available.

With the increased energy requirement for short or long intensive physical exertion, there is an additional requirement compared to the DACH references, which must be quantified individually according to energy consumption. Sport-associated micronutrient losses (sweat loss), exercise-related additional requirements, and critical supply phases (environmental conditions, individual eating habits, appetite regulation, weight reduction) run parallel to intensive physical activity. In particular, the loss of minerals through sweating is individually variable. The sodium content of sweat has an average of 874 mg/l, but the range is 175–1512 mg/l. For the minerals Ca, Fe, K, Cu, Mg, and Zn, the losses are far less high, but they also have a wide range in variation (Brouns et al. 1992).

Examples of a mineral requirement for athletes calculated based on the DACH reference values are given in ▣ Table 18.10. The extrapolation of the average energy requirement of male adults to different energy consumption is very different from the recommendations, for which no scientific citations are given. When sweating, the mineral supply must be dosed higher according to the sweat losses.

To achieve the best oxygen update, a high ferritin and free iron in the blood is needed; supplements of Fe and Vitamin B12 should be taken early in training. As well as to aid ATP synthesis by mitochondrion, a consumption of CoQ10 (Vitaminoid) and PQQ (Pyrrolochinolinchinon) might be helpful for higher energy production. Additionally, the intake of Nattokinase, which helps for good blood flowing, could stimulate a good blood supply!

▣ **Table 18.10** Mineral requirements of athletes with high energy consumption based on the DACH references

Men aged 5–51 years	**DACH references (2008)**					**Recommendation (Carlsohn et al. 2019)**	
Energy	**2900 kcal/d**	**1000 kcal**	**3500 kcal**	**4500 kcal**	**5500 kcal**	**per day**	**Metabolism**
Na (mg/d)	550	190	664	855	1045	4000–8000	Muscle function, water supply
Se (mg/d)	70	24	85	110	133	100–200	Antioxidants, thyroid, regeneration
Mg (mg/d)	400	140	480	620	760	200–600	Muscle function, nerve conduction velocity
Fe/Zn (mg/d)	10	3.5	12	16	19	20–40	Oxygen transport, immune system, protein synthesis
P (mg/d)	700	240	845	1090	1330	2000–4000	Muscle function, energy turnover

Carlsohn et al. (2019)

With a well-planned whole food diet for the intended physical activity, when ascending to altitude, the mineral requirement can be well covered with sufficient nutrition. However, with the loss of appetite at altitude and the reduced energy intake, performance-impairing deficiency situations can occur in as little as a week and manifest themselves with AMS symptoms and lower oxygen saturation, and, if prolonged, they can also trigger significant health disorders.

One-sided eating habits lead to deficits, such as a preferential plant-based diet causing an undersupply of zinc. Zinc is less well absorbed, as fibre and phytate complexes form that are difficult to dissolve and absorb. The foods oatmeal, whole grain cereals, brown rice, legumes, nuts, and pumpkin seeds, for example, contain a lot of zinc. But important suppliers with easily absorbable minerals are meat, dairy products, and eggs. A combination of whole grain cereal products with dairy products promotes zinc absorption.

18.9.7 Vitamin Requirements on the Mountain

At high and extreme altitudes, an abundant availability of fat-soluble (A, D, E, K) and water-soluble vitamins (C, B1, B2, B6, B12, niacin, folic acid, pantothenic acid, biotin) is important, as they are jointly responsible for the function of energy, protein, and carbohydrate metabolism, the function of the nervous system and the immune balance.

In the usual whole foods, the daily consumption of five portions of fruit and vegetables, about 700 g/d, is recommended, which cover the vitamin requirement well. Due to the environmental factors and the stress at an altitude above 3000 m, an undersupply during the stay of 2–3 weeks can have a strong negative impact on performance, metabolism, and the immune system. During long trekking trips, with limited consumption of fresh plant-based foods and intense physical exertion, a vitamin deficiency can lead to health impairments and AMS. This is especially the case if the previously usual diet has not been attentive to an optimal whole food diet for a long time. With shorter one-week tours and good daily nutrition, no risks are to be expected.

Due to high physical exertion, low fresh food, UV light, and ozone, “free radicals” (aggressive oxygen compounds) are formed at high altitudes. These oxidatively attack and destroy the body’s own structures (proteins, carbohydrates, lipids, and nucleic acids) if they are not insufficiently inactivated. Antioxidant vitamins (vitamins C, E and provitamin A) from plant-based foods prevent this metabolic damage. In addition, vitamin C promotes the absorption of iron and thus erythropoiesis for optimal oxygen supply at altitude. At altitude, it is likely that there will not be enough fruit and vegetables available for logistical reasons. A high vitamin intake with supplements protects against deficiency but does not lead to an increase in performance. B vitamins are involved in the metabolism of carbohydrates (vitamin B1, niacin), fatty acids (niacin), and amino acids (vitamin B2, B6, niacin) for energy production. The high supply of carbohydrates during intensive activity on the mountain requires a higher intake of vitamin B1. This also plays a major role in the transmission of nerve impulses in the brain, in the peripheral nerve cells, in collagen synthesis and is therefore also important for wound healing. Many B vitamins are obtained from the consumption of whole grain products (bread, rice, pasta) and vitamin B2 (riboflavin) also being in milk and dairy products. A sufficient vitamin D supply (serum level > 75 nmol/l, optimum approx. 100 nmol/l) is essential for muscle strength, performance, and immune function in sports.

Vitamin D seems to have beneficial effects on muscle structure, cross-section, and the number of type II muscle fibres; it gives protection against myopathies and regeneration.

Upper respiratory tract infections are common when blood levels are low. Vitamin D deficiency also worsens iron status and increases the risk of anaemia. A check of the blood values about 2 months before the high-altitude tour is useful to advise supplementation for several weeks (1000–2000 IU/d, 25–50 μg/d possibly together with Zn, Se) in those with low serum concentration (<75 nmol/l, 30 mg/ml).

Vitamin D is stored in fat and muscle tissue, where it lasts a long time. Nevertheless, vitamin D supplementation seems to make sense during high physical exertion as individual self-synthesis of vitamin D varies greatly according to age, skin type, season with little sun-skin contact. High-dose dietary supplements (NEM) with >4000 IU of vitamin D/d (100 μg/d) should not be used. There are only a few foods that contain significant amounts of vitamin D (◘ Table 18.11): fatty sea fish (e.g. salmon, herring, mackerel), egg yolks and some edible mushrooms. To meet the high demand with food alone, a lot has to be consumed, which is not possible with normal food, especially on tour.

Dietary supplements must therefore be planned for a longer wholesome diet at altitude, and their individual compatibility must be tested. For long tours at high altitudes, the intake of vitamin supplements (dietary supplements NEM) should be planned, as the high demand can hardly be covered logistically with fresh food. This should be realised during the rest days in the base camp before and immediately after the tour. The vitamin supply is extrapolated in relation to the calculated energy consumption according to the planned activity based on the DACH references for 2500 kcal/d and supplemented if the actual energy supply is deficient for more than a few days. Higher doses of the antioxidant vitamins C and E as well as vitamin D are taken to prevent special risks at altitude.

◘ **Table 18.11** Vitamin D and polyunsaturated fatty acids (PUFA) in food

	Vit. D (IE/100 g)	Vit. D (μg/100 g)	PUFA (g/100 g)
Fish oil, cod liver oil	10,000	250	22.5
Mackerel, salted	1008	25.2	6.2
Mackerel, Atlantic, spirit	645	16.1	2.63
Hering, sour	480	12.0	2.65
Salmon, Atlantic Ocean, sigh, raw	440	11.0	4.2
Sardine, raw	440	11.0	1.62
Salmon, wild, raw	336	8.4	4.2
Yolk, raw, fresh	216	5.4	5.25
Lamb, chop, raw	208	5.2	0.15
Penny bun, steamed	152	3.8	
Cream cheese	108	2.7	0.14
Chanterelle, steamed	104	2.6	

► www.lebensmittel-naehrstoffe.de, Nährwerttabelle

18.10 Nutrition Planning for the Tour into the Heights: Strategic Eating and Refueling

For mountain hiking, mountaineering, and climbing (alpine sports), nutrition planning is very different. The mountain hiker does his activities occasionally and is not exposed to training with constantly high physical demands and physical loads at high altitudes. Mountain hiking is walking in mountainous terrain, of longer duration and higher physical intensity than walking.

To assess the intake demand estimation, it is expected that you can reach a maximum walking speed of 5 km/h and be able to keep up this for several hours to about half a day. For example, the daily energy and nutrient supply for a wholesome diet under physical exertion is based on the general DACH guidelines. For a longer trip up the mountain (>1 h), a good hydration (1–2 l) and a carbohydrate meal for half a day (4–5 h) are necessary. Recovery takes place with whole foods back at home or in the base camp.

As a basic requirement of daily food energy (without any sporting exertion (◘ Fig. 18.2)), an energy requirement of 2800 kcal/d would be expected for a young adult of approximately 80 kg body weight, 15% body fat, for 4–5 h of light physical activity per day with a PAL = 1.4. This is the daily amount of energy intake taken as three main meals and two snacks, with which experience has shown that you maintain your weight constantly.

> ❯ For a half day, sporty mountain hike, you need almost as much food as you can consume per day in a less active everyday life.

In contrast, mountaineering involves a significantly higher, regular, physical strain on the alpine athlete. The "high-altitude mountaineering" with altitudes above 4000 m and the need for regular training with an intensity that comes close to the ascent to altitude and the stay in the base camp. In addition, the significantly reduced air pressure at altitude leading to reduced oxygen supply needs a physical adaptation, which also requires special nutrition planning.

18.10.1 The Training Time Before the Tour

As a basis for nutrition planning, it is necessary to determine the daily energy requirement. This is estimated for the mountain tour with the daily protocol of the heart rate of a test tour (► Sect. 18.7, ◘ Table 18.1), and then the proportions for the usual five daily meals are divided (◘ Fig. 18.2, ◘ Table 18.12). Longer (mountain) hikes over several days and a longer distance require food logistics that cover the entire daily requirement, including the daily walking requirement.

For mountain tours lasting several days, e.g. with 5 h of high activity per day, a basic requirement of about 2800 kcal/d and the additional requirement according to the PAL-value based on the HF test are required for the ascent.

For example, intensive walking at 5 km/h consumes about 200–250 kcal/h. A 5-h ascent—about the same heart rate as fast walking—consumes about 1000–1250 kcal in addition to the basal daily requirement, which must be covered with two plentiful main meals and 2–4 smaller snacks before the start (breakfast), during the ascent and after the approximately 5 h walk (◘ Fig. 18.2) on the mountain. The backpack supply takes up about 50% of the total requirement. This could be covered with relatively small "power bars" for example (◘ Table 18.12). Alternatives for one of these bars would be, for example, 18.2 slices of wholemeal rye bread with cheese or ham

Meal distribution for basic requirement		Meal distribution according mountain base camp	
	Breakfast 25%E		Breakfast 25%E
	1. Snack 10%E		1st Backpack snack 10%E
	Lunch 30%E		2nd backpack snack 15%E
	2. Snack 10%E		3rd backpack snack 15%E
	Dinner 25%E		2nd hut snack 10%E
Active Day 2800 kcal/d		5-hour mountain tour 4800 kcal/d	Dinner 25%E

Fig. 18.2 Recommended meal distribution based on daily energy requirements. (data in Table 18.12; E energy)

Table 18.12 Meal distribution for a normal basic requirement day and a mountain tour day based on the estimate of energy demand (E = energy)

Active day	2800 kcal/d	5-h mountain tour	4050 kcal/d	For example
Breakfast 25%E	500 kcal	Breakfast 25%E	1013 kcal	
1st snack 10%E	280 kcal	1st backpack snack 10%E	405 kcal	Two power bars
Lunch 30%E	840 kcal	2nd backpack snack 15%E	608 kcal	Three power bars
2nd snack 10%E	280 kcal	3rd backpack snack 15%E	608 kcal	Three power bars
Dinner 25%E	500 kcal	2nd hut snack 10%E	405 kcal	Two power bars
		Dinner 25%E	1013 kcal	

or for two bars about 300 g of vegetable risotto in a plastic box (Table 18.13).

The full-fledged nutrient supply is to be achieved by selecting foods according to the proposal of the nutritional cycles (Figs. 18.1, 18.2, and 18.3). No food contains all the necessary nutrients on its own. With the selection per day and per week suggested in the food cycles, the full-fledged supply is ensured and the weight can be kept constant. For whole foods, plant-based foods (cereals 31% of E, vegetables 25% of E, fruit 17% of E) (► Sect. 18.8) provide the main share of energy and nutrients with about 73% and about 25% of E animal-based foods ensure wholesomeness. These

Table 18.13 Selection of optimal foods for the mountain tour day (DMF dry mass fat)

Food group	Selection
Whole grain cereal products, pastries	Cereal muesli with (dried) fruit and low-fat whey powder; muesli bars, whole grain products (rolls) made from cereal mixtures
Skimmed milk products	Milk and yogurt (≤1.5 g% fat); hard cheese (≤45% DMF), quark (Topfen) 10% DMF; spreads ≤20% DMF
Fruit, vegetables	For example, tomato, cucumber, kohlrabi, carrot, fresh or frozen, in one piece or unsweetened preparations (puree)
Meat/fish (goods), eggs	Ham (without fat rim); Turkey breast, fillets of mackerel, salmon, hering; Omega-3 egg
Beverages	Water, mineral water, all-natural fruit juices, isotonic sports drinks, coffee, unsweetened tea (fruit tea, green tea, black tea)
Spreadable fats	Use sparingly, better omit!

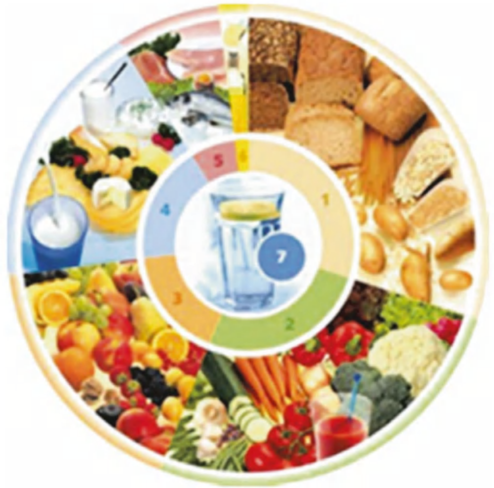


Fig. 18.3 DGE nutrition cycle: groups for basic nutrition (food groups 1–7)

ratios are to be achieved both for training nutrition and during a week's stay and longer in the base camp at altitude. The quantities of the different food groups must be adapted to the energy requirements for activity at altitude.

The quantities in the DGE food cycle are given for an energy requirement of about 2500 kcal/d. According to the estimated energy requirement for activity in the altitude in relation to DACH recommendation, more of these quantities should be planned for at the base camp and during mountain tour. For the calculated 4000 kcal/d at altitude, 60% more food needs to be chosen according to the food pyramid.

The DGE Nutrition Circle (Fig. 18.3) (DGE 2015) provides a quantitative outlook on the food groups of what a healthy and ecologically sustainable diet looks like. The size of the food groups angle in the circle illustrates as a guide the share they should take in the diet. The larger a food group is, the more can be eaten. It is recommended to use the variety of foods within the groups and to eat a varied diet.

For the basic diet according to the recommendation of the DGE nutrition group (Fig. 18.3; ► https://www.dge.de/gesunde-ernaehrung/dge-ernaehrungsempfehlungen/dge-ernaehrungskreis/), the following amounts of the six food groups from the nutrition cycle are to be consumed in average per day weekly.

- Cereal products and potatoes are the largest food group. Whole grain products are preferable. About 250 g of bread and 60 g of muesli flakes, 200 g of boiled potato or 200 g of wholemeal pasta or

150 g of cooked brown rice instead would be the target sizes of this group.

> Whole grain cereal products, especially oats, amaranth, quinoa, contain many minerals and B vitamins.

- Of the vegetable group, three portions (approx. 400 g) per day would be worth eating fresh or gently cooked in steam or with the microwave. Legumes such as lentils, soybeans, lupins are plant-based protein alternatives with 60–100 g per serving.
- In addition, there are two servings of fruit (approx. 250 g). Nuts (30 g) can replace one serving. They contain plenty of monounsaturated and polyunsaturated fatty acids, vitamins B and E, magnesium, potassium, iron, zinc, and secondary plant substances.

> All vegetables and fruits provide carbohydrates, prebiotic fibre, vitamins, minerals, and secondary plant substances. Leafy vegetables and salads also contain important minerals.

- Dairy products are available in a wide variety, so that daily enjoyment with low-fat milk drink (≤1.5% DMF milk, yoghurt, kefir, buttermilk) and approx. 60 g cheese (30% DMF) is easily possible.

> Dairy products with plenty of various microbiotic cultures (Bifidus, Lactobacillus, etc.) are preferred for the care of the intestinal flora.

- Low-fat meat (fillet, rump) should be in the diet plan weekly with approx. 300 g for normal and approx. 600 g for high energy requirements. In addition, one portion (150 g) of lean sea fish (cod, redfish) and one portion (100 g) of fatty marine fish (salmon, mackerel, hering) as well as three eggs a week.
- Consume 1–2 tablespoons of the valuable oils (rapeseed, soy, walnut, green pumpkin seeds) daily. Together with the vegetables or directly from the spoon. Butter and margarine only if you are not able to do without them.
- Margarine only with a higher content of polyunsaturated fatty acids (omega-3 PUFAs)!

> Marine fish or virgin linseed, rapeseed or walnut oil contain important omega-3 fatty acids.

18.10.2 Preparation for the Tour

The nutrition plan for high mountains requires information about food logistics in the tour region about the possibilities to obtain a whole food diet. To compensate for an undersupply, ready-made or easy-to-prepare meals can be prepared or procured. Today, there are meals packaged by sports and food retailers that can be kept in stabile bags and are easy for transport (■ Tables 18.14, 18.15, 18.16). To be eaten, these are warmed in-the-bag in a water bath or prepared with warm water and are then ready to eat. The information for the CH and protein content can be seen from the sachet nutrition table. Classic vegetable products (white cabbage, pickled cabbage, red cabbage) in a sturdy foil bag are good suppliers of minerals and fibre for intestinal flora care, and they can be eaten cold or warm.

Root vegetables (beetroot/beetroot, carrots) are also available in transportable packaging. Ready-made vegetable juices (vegetable juice mix, carrots, tomatoes) are good sources of minerals and vitamins. With 100 ml, the normal half daily requirement can be partially covered.

The predictable supply of self-prepared food provides a good alternative to sufficient tour nutrition and for staying at altitude.

Individual portions for individual meals containing cooked wholemeal pasta, pota-

Table 18.14 Vegetables and fruit to take away (warming only)

Vegetable per 100 g		Energy (kcal)	Fat (g)	Sat. FAc (g)	Unsat FAc (g)	CH (g)	Sacch (g)	Fibre (g)	Pro-tein (g)	Salt (g)	Vit C (mg)	Vit B1 (mg)	Fe (mg)	Mg (mg)
Red cabbage with apple	70% Red cab., 6% applesauce	44	0.5	0.1	0.4	8.4	8.3	1.9	1.1	1.3	50			
Sauerkraut	White cabbage sliced and gurged	17	0.5	0.1	0.4	0.6	0.6	1.9	1.4	1.3	20			
Beetroot cooked	Red root	46	0.5	0.1	0.4	8.4	8.4	3	1.5	0.7	10			
Redroot salad	Root, vinegar, saccharin	24	0.1	0.1	0	4.6	2.8	3	0.8	1.1	10			
Red cabbage	85% cab., applejuice, vinegar, salt, onions	44	0.5	0.1	0.4	8.4	8.4	2.6	1.3	1.1	8			
Sunflower seeds		609	49	5.3	43.7	12	1.7	6.3	27	0		2	6.3	420
Pumpkin seeds		582	46	9.4	36.6	2	1.4	6	37	0			13	402
Plum roaster	70% plum, sugar, citric ac.	99	0.1		0.1	24								
Apricot roaster	71% apricot	80	0.1		0.1	19	4	2	1		5		0.5	7

If hygiene conditions are observed during preparation, the shelf life of the self-made trekking fabric is sufficient. Muesli with cereal flakes, seeds (sunflower seeds, pumpkin seeds), nuts, fruits (dry or fresh) can be made according to individual preference and mixed with skimmed milk powder, so that on the mountain only water is needed to have a carbohydrate-rich meal at breakfast or after the intensive high-altitude tour

Table 18.15 Ready meals to take away (warming only)

Ready meals per 100 g		Energy (kcal)	Fat (g)	Sat. FAc (g)	Unsat FAc (g)	CH (g)	Sacch (g)	Fibre (g)	Prot (g)	NaCl (g)	Vit C (mg)	Vit B1 (mg)	Fe (mg)	Mg (mg)
Hering fillet in tomato sauce	60% hering, 14% tomato paste, raps oil, sugar	182	12	2.1	9.9	4.5	3.8	1.1	13	0.8				
Red beans	Beans, salt	92	0.6	0.1	0.5	12	0.4	6.7	6.5	0.9	1			
Whole wheat pasta	Whole grain hard semolina	351	2.5	0.5	2	67	3.5	6	12	0				
Penne with mushrooms	78% pasta, sunflower oil, milk protein, 1.2% champ.	389	7.7	1	6.7	66	5.7	2.8	12	3.7				
Rapeseed oil	Rapeseed oil pressed	824	92	6	86	0	0	0	0	0				
Safflower oil	Safflower oil pressed	828	92	7.3	84.7	0	0	0	0	0				
Olive oil	Koroneiki olives	828	92	14	77.2	0	0	0	0	0				

Table 18.16 Packaged ready-made trekking food (travel lunch, prepared with water; values per 100 g)

Per 100 g	Risotto and asparagus and broccoli	Vegetarian tandoori and quinoa	Spinach potato pot	Pasta in tomato-sauce	Beef Stroga-noff	Vegetable party
Energy (kcal)	110	170	404	460	540	377
Fat (g)	3.1 (27%E)	3.8 (21%E)	14 (32%E)	9 (18%E)	18.8 (32%E)	12.3 (30%E)
Sat. fatty ac. (g)	0.6	0.5	8.9	5.4	12.5	2.8
Unsat. fatty ac (g)	2.5	3.3	5.1	3.6	6.3	11.5
Carbohydrate (g)	17 (65%E)	24 (58%E)	57 (58%E)	78.8 (70%E)	73.8 (56%E)	30.4 (33%E)
Saccharose (g)	0.8	4.0	8.4	17.5	4.0	7.5
Protein (g)	2.9 (11%E)	5.0 (12%E)	9.7 (10%E)	11.8 (11%E)	16.3 (12%E)	31.2 (34%E)
Salt (g)	1.45	0.8	3.7	5.4	4.4	5.8
Pack (g)	400	400	125	125	125	500

toes, boiled brown rice, or vegetables (green beans, peas, sprouts, Brussels sprouts, carrots, celery, parsnips) can be filled warm into freezer plastic bags (Ziploc bags), and then with the air sucked out, they can be sealed with a welding machine. The bags can then be warmed in a water bath to about 70 °C making the method well suited for meal preparation at altitude. A home-cooked trekking menu has an individual taste, is inexpensive, and is free of additives (cookbook "Rucksackküche"– Backpack Kitchen)! With canned goods of herring fillet in sauce, sardines in rapeseed oil, tuna, salmon, meat or vegetables (red or white beans, peas) in rapeseed oil or sauces, menus with special carbohydrate or protein content are then easily available to meet individual needs for different situations at altitude. The ready-to-eat products have an energy content of approx. 150–250 kcal/100 g and then result in a meal of approx. 600 kcal cooked with a portion of wholemeal pasta (300 g, 420 kcal) and thus about 15% of E of the daily requirement.

For extreme exertion, 8–12 g CH/kgd (70 kg, 700 g CH) should be available in the daily meal plan. With 100 g of muesli mix, about 60 g of carbohydrates, 8 g of fibre, and about 350 kcal can be consumed, which can provide the necessary glycogen storage. The prepared muesli portions are also shrink-wrapped in plastic bags. With spray-dried whole egg powder (protein 44 g/100 g with high BW, 590 kcal/100 g) and water, you can easily prepare a scrambled egg for protein supply. Ready-made, dry muesli mixes in a bag are good to use for meals during the tour when water is available.

The finished trekking foods (Table 18.16) come quite close to the guidelines with their ratio CH:P:F. On the

Internet, many ready-made trekking foods can be found with "travel lunch" or "trekking food". Freeze-dried products offer the advantage of a very good energy-to-weight ratio and an optimal nutrient supply and are quick to prepare. The optimal proportions of the main nutrients should be CH 60% of E, fat 20% of E, protein 20% of E. With a good nutrition plan, the weight of a daily ration will range between 600 and 1000 g, which shows the limits of a backpacking trip. For a two-week self-sufficient tour, you have to reckon with up to 14 kg weight for the tour catering! Weight reduction through savings is not advisable!

The planned ready-made and self-prepared trekking menus for the altitude are to be tested for their tolerance and usability under extreme physical stress, as gastrointestinal disorders are more likely to occur at altitude (e.g. feeling of fullness, heartburn, gaseous distension, diarrhoea), accompanied by extensive impairment of performance. The diet at altitude should not differ much from the usual eating habits because of the tolerance. Freeze-dried foods (trekking food) help to be successful as energy-rich, light food for tours at high altitudes.

Studies of the eating habits of alpinists at high altitudes showed that the measured energy requirement of 4560 kcal/d was only covered by 60% due to the loss of appetite. At the same time, the protein supply was too low and the fat consumption too high. An analysis of double-labelled water energy expenditure among Mount Everest climbers shows that energy expenditure during physical activity is 1.85–3.0 times higher than resting energy expenditure at sea level (Westerterp-Plantenga et al. 1999).

> There is a need to develop a nutrition plan for the stay at altitude that, if consistently adhered to, ensures well-being and physical performance. This nutrition plan must be tested practically before the planned tour to the heights to ensure tolerance.

18.10.3 Nutrition During Adaptation and Recovery in Base Camp

The timing and composition of the meals consumed can play a role in optimising performance, training adaptation, and avoiding overtraining.

Anyone who is planning a tour or wants to organise and lead it themselves would do well to deal intensively with the laws of altitude and acclimatisation and to find out about the special forms of mountain sickness. Everyone should observe the laws of altitude; otherwise, they are threatened with a "breathtaking adventure" in the truest sense of the word. For acclimatisation, a phase of at least 2 weeks seems to be necessary before one can manage the ascent to the extreme altitude without metabolic problems.

On the day of the tour, the breakfast should be planned to be carbohydrate rich to replenish the glycogen stores that might been reduced since dinner and to ensure a good blood sugar supply until the first snack 2 h before the start. The approximately 1000 kcal for breakfast (◘ Table 18.12) should contain 60–80% CH-Oligo-Polysaccharides, i.e. about 200 g. In oatmeal muesli with dried fruit (e.g. apple, apricots, cranberries, dates, peanuts, chestnuts, pumpkin seeds, or similar), there are already about 70 g CH, 10 g protein, and 350 kcal available in 100 g. Two slices of wholemeal rye bread (120 g) provide an additional 230 kcal and 50 g CH.

18.10.3.1 Stabilisation of Lean Body Mass at High Altitude

Results of a survey showed weight loss in 73.3% of mountaineers returning from an expedition. During a one-week stay at about 4000 m, mountaineers lost about 3% of their body weight and at extreme altitudes of 5300–8000 m 15% after 3 months (Westerterp-Plantenga et al. 1999). These losses are not body fat only but muscles as well!

Loss of lean body mass negatively affects the body's aerobic capacity (Hoppeler et al. 1990), muscle strength (Brouns et al. 1992), and immune functions at high altitudes, which can increase the risk of disease (AMS) and injury under these extreme conditions. Possible causes of altitude-induced muscle wasting are reduced muscle protein synthesis and suboptimal energy and protein intake. A negative energy balance—often due to loss of appetite—is the main cause of catabolism of muscle proteins. After depletion of glycogen and fat stores, protein stores are catabolised to cover energy consumption (Ocobock 2017).

Even a high protein intake only promotes effective protein synthesis to secure lean body mass if the energy requirement is balanced. For a diet plan with sufficient energy (at least 27–30 kcal/kg) and protein (1.6–1.8 g/kg/day), an additional protein dose (0.25–0.40 g/kg per dose) should be considered every 3–4 h during the tour day at altitude during intense physical activity. Nutritional interventions with carbohydrate + protein or protein alone, before and after the day tour, can support an effective improvement in body composition.

It seems physiologically reasonable to consume an additional dose (0.25–0.40 g/kg; 2.3–3.1 g/kg lean body mass daily) of high-quality protein 2–3 h before and within an hour after the tour in order to stimulate muscle protein synthesis to the maximum. The use of a leucine-rich protein supplement (700–3000 mg/d) seems to be useful to protect against the breakdown of lean body mass at high altitude (Wing-Gaia 2014).

A small dose of tryptophan (1 g) can improve both mood and sleep quality. Foods high with tryptophan include nuts (cashews, walnuts, peanuts, almonds), sesame and pumpkin seeds, soybeans, and cereals.

> Staying at high altitude (>3000 m), even without physical exertion, leads to weight loss due to loss of appetite with about 1/3 less energy intake. Then 2/3 of body fat and 1/3 of lean body mass are lost (Armellini et al. 1997).

18.10.3.2 Tour Catering for Alpine Athletes

Personal experiences from alpine athletes on nutrition during an excursion diverge very widely. Physiological considerations, the estimated energy requirement, and test experience with the nutrition plan at altitude should form the basis for the backpack catering. For a day tour, about 50% of the daily energy requirement (◘ Fig. 18.2) is necessary at altitude. During intense physical exertion at altitude, CH consumption can increase up to 80% of the total energy. For endurance performance on the mountain tour, a carbohydrate-rich diet (75% CH) is recommended, e.g. with wholemeal bread, dried fruit, fresh fruit, bananas, fruit slices, muesli, or muesli bars.

At breakfast 2–3 h before the start of the tour, good carbohydrate stores should be built up in the body and replenished during the day with snacks and dinner. To ensure optimal physical and mental performance during the day, energy reserves should be replenished repeatedly after a plentiful, easily digestible breakfast (25% of daily energy; ◘ Fig. 18.2). The breakfast is used up in the first 3 h of heavy physical exertion.

Starchy foods ensure a moderate but longer-lasting increase in blood sugar. Pure glucose causes rapid high blood sugar spikes and should therefore only be used in small quantities (approx. 50 g), when glucose is needed acutely (glucose tablets, dextroenergen).

The carried food must cover the current consumption during the tour after breakfast until dinner with 3–4 snacks (◘ Fig. 18.2, ◘ Table 18.12). Each snack of 400–600 kcal is necessary, which are covered in short breaks with a small carbohydrate meal (fruit muesli) and drinking or by power bars (muesli bars) and drinking while walking. Wrapped in tortillas (wraps), vegetables, salad and meat (ham), quark can make good snacks. The reduced appetite at altitude must be ignored; eat according to the plan! As long as people eat, even against loss of appetite, the risk of a drop in performance is low. However, 1000 m of altitude gain or more without meal breaks or without mountain-appropriate snacks is risky. Four slices of wholemeal rye bread with ham or cheese (without spreadable fat) are also acceptable meals with a break to chew intensive and to drink water or tea (without CH).

Nuts, dark chocolate, dried fruit, dried vegetables, energy bars, cooked rice, oatmeal, couscous, lentils, flaxseed, chia seeds, and similar can be combined perfectly and provide plenty of energy and beneficial nutrients for the day.

> In the case of prolonged intensive endurance exercise, especially at high altitudes, conscious eating is necessary to keep to the plan including rest phases—practical for recovery and for storage in liver and muscle storing.

Improved cognitive and physical performance was observed with the use of caffeine tablets at 3–6 mg/kg (McLellan et al. 2016).

The hypobaric hypoxic conditions at altitude are accompanied by oxidative stress. The intake of antioxidants with food can counteract oxidative stress. High dosages (vitamin C up to 200 mg/d) seem to be necessary at altitude and can prevent a cold. For a safe iron supplement at altitude, combined with vitamin C, a supplement with 40–60 mg/d would be beneficial.

> For a half-day tour, you should pack about twice as much food for the snack as is needed for breakfast.

After the strenuous mountain tour, a relaxing warm dinner (vegetable soup, vegetables) within an hour of arrival is the best reward and a good rest. Ready-made pasta or potato menus restore glycogen and energy reserves (◘ Table 18.15). A hearty stew with pasta (cheese spaetzle), meat, mushrooms, and onions, a rice dish with vegetables and fish or foil jacket potatoes with quark can simply be infused with hot water in the trekking menu bag (Ziploc bag), drink plenty of fluids to improve regeneration and prepare for the next day. The choice of ready meals is dominated by the available mountain cooker! Appetising trekking tour meals are available from our own kitchen or from several manufacturers as a ready-made product. In the evening, however, only eat enough for sleeping well afterwards.

18.10.3.3 Water Balance: Hydration

Drinking too little is far more critical than eating too little: Hydration is very important for performance. Feeling thirsty is not a sure indicator of the necessary fluid intake. Fluid is often necessary for the metabolism in several smaller portions (approx. 1/4 l each) before a pronounced feeling of thirst develops. Also, larger quantities of fluid take more time to pass the stomach. Warm drinks are better than cold ones.

For very high loads, it is recommended to consume about 90 g/h of easily usable CH (oligosaccharides, maltodextrin). This can be done every 15–30 min in combination with water, with 6–8% CH electrolyte solutions, to promote euglycaemia. At least 1.5 l of drink is required for the necessary CH and about 3–5 l of drinking for an extreme day tour. In addition to water, the CH drink can also be prepared with tea (black tea, fruit tea) or weak coffee, the caffeine of which has been observed to have an ergogenic effect.

Light black tea and tasty fruit tea with sodium and maltodextrin are good for replenishing liquid. Isotonic beverages on the market (approx. 250–340 mosmol/kg) usually contain low-molecular carbohydrates, which have a rapid effect on blood sugar and are thus suitable for rehydration, but less well suited for longer carbohydrate supply to refill liver and muscles.

For the restoration of the normal state of hydration after diarrhoea, solutions containing approx. 60 mmol/l Na (3.5 g/l NaCl) and approx. 120 mmol/l glucose (20 g/l) are used. Care must be taken to ensure that sodium and glucose are contained in this quantity and ratio. To keep the osmolarity of a drink low (<300 mosmol/l) and thus achieve better tolerability, glucose is better replaced by the glucose polymer maltodextrin.

18.11 Dietary Guidelines for Mountain Athletes

- Compensation for balance deficits: water, energy, carbohydrates, protein
- Balanced energy supply:
- * Maintaining performance
- * More efficient energy production from high-molecular carbohydrate-rich foods: rice, potatoes, pasta dishes, maltodextrin-containing beverages
- * Striving for a constant body weight (protein supplementation)
- Liquid: Compensation for losses! Striving for a constant body weight.
    - Weight control in the base camp!
- Optimal protein intake: Foods with animal (for iron intake) and vegetable protein combined in a ratio of 1:2
- Fat reduction: poorer fat tolerance at altitude, especially animal fats.
    - Vegetable fat supply to care for UFAc intake!
- Optimal energy ratio of the main nutrients: Protein:Fat:Carbohydrate = 18%E:15%E:67%E
  (protein- and carbohydrate-rich, but low-fat food)
- Diet rich in active ingredients: Selection of mineral-rich (K, Mg, Fe) and vitamin-rich foods
- Stable immune metabolism: Antioxidants in vegetable foods and nutritional supplements (vitamins C, D, E)
- Light whole food: easy to digest, well tolerated
- Avoid alcohol! Increased risk of altitude sickness

18.12 Organisation of Nutrition for a Tour over 2500 m

There are three different mountain height levels, each of which requires a separate adjustment.

1500–2500 m (medium altitudes): Immediate adjustment is enough! Diet according to the guidelines for whole foods! Below 1500 m there are usually no health impairments. The average altitude of about 2500 m is the area where altitude training can be completed during tour training.

At higher altitudes of 2500–5300 m, immediate adjustment is not enough. The decrease in the oxygen partial pressure and thus the decrease in the oxygen available to our body in the inhaled air begin to influence the metabolism from the threshold height of 2500 m. From here upwards, acclimatisation time (weeks) is required for the main area of trekking tours!

An altitude level of 3500 m is the acclimatisation range in which performance at extreme altitude can be ensured by a 2-week stay with training and adapted nutrition. This can be increased with several steps of 500–1000 m. Maintaining lean body mass and the availability of glycogen through a high-carbohydrate diet are required. Above 5500 m, however, a complete adjustment to the altitude is not possible. This border leads to physical and mental deterioration and a loss of performance if the stay is longer than a few days.

High-altitude mountaineering is certainly a fascinating sport, stressful but relatively harmless, if the laws of altitude are observed and the body is given time to adapt to the altitude by training and optimal nutrition planning. It is important to notice appetite loss and any health impairments and symptoms, such as headaches, unsteady gait, shortness of breath, and reduced urine output within 24 h (less than 500 ml).

> Nutrition and nutritional planning for the tour to extreme altitudes are just as important as continuous physical training.

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19

The Impact of Altitude on Physical Performance

Martin Burtscher, Mahdi Sareban, and Gunnar Treff

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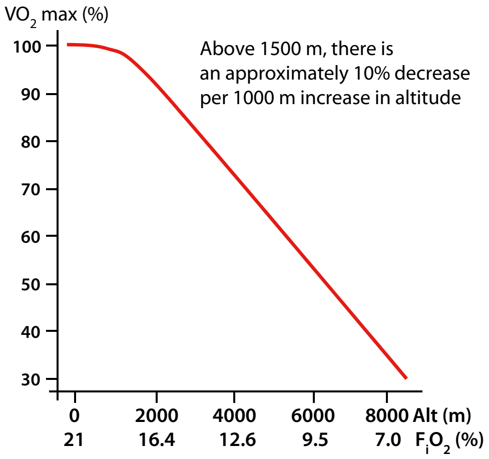
Individual endurance capacity is a key determinant of performance in mountain sports. Aerobic capacity ($\dot{V}O_2$max) is a critical component of endurance performance. As the barometric pressure decreases with increasing altitude, resulting in a corresponding reduction in the partial pressure of oxygen, a continuous decline in $\dot{V}O_2$max of approximately 6–10% per 1000 metres of altitude is inevitable. At altitude, gas exchange may become a limiting factor even at a moderate workload and at all work intensities, and the cardiovascular system is subjected to greater strain. In addition to hypoxia, cold, the extra weight of a backpack, safety equipment, and footwear also affect endurance performance at altitude. Good physical conditioning, sufficient acclimatisation, many years of experience in mountain activities, and appropriate equipment are essential prerequisites for high endurance capacity at altitude and thus for the success of high-altitude expeditions. In order to identify risk factors and enable a targeted training, health status and physical performance should be assessed as part of a sports or high-altitude medical examination 6 to 12 months prior to a high-altitude expedition. An additional check-up immediately before the expedition then allows for an evaluation of training success.

Aerobic, i.e. oxygen-dependent, energy production is necessary to maintain many metabolic processes in the human body. When energy expenditure increases due to physical activity, such as mountaineering, aerobic energy production and thus oxygen consumption also increase. Oxygen consumption during exertion is finite, and its maximum value is referred to as maximal oxygen uptake ($\dot{V}O_2$max) or aerobic capacity. As the oxygen supply per breath is progressively reduced with increasing altitude, $\dot{V}O_2$max also decreases in a characteristic manner (◘ Fig. 19.1). If $\dot{V}O_2$max is already low at sea level, the further altitude-related reduction may significantly limit ascent speed even at moderate altitudes. Conversely, a high $\dot{V}O_2$ max at sea level may enable ascents of peaks above 8000 m even without supplemental oxygen. Thus, there is a close relationship between $\dot{V}O_2$ max measured at sea level and performance capacity at altitude. Mountaineers with high $\dot{V}O_2$max, provided they tolerate altitude well, are generally more efficient at altitude. However, as with endurance performance at low altitude, sustained performance capacity and movement economy also play a very important and potentially a decisive role in high-altitude expeditions (Burtscher et al. 2008; Joyner and Coyle 2008).



◘ **Fig. 19.1** Decline in maximal oxygen uptake ($\dot{V}O_2$max) with increasing altitude (Alt) or decreasing inspiratory oxygen concentration (F_iO_2). (Modified after Cerretelli 1992)

These factors depend directly or indirectly on the actual altitude reached and the level of acclimatisation, as the altitude-related reduction in $\dot{V}O_2$max improves by 5–13% over a period of 15 days to 10 weeks (Furian et al. 2022). Additional training under hypoxic conditions further enhances these beneficial acclimatisation effects (Millet and Jornet 2019). Track and weather conditions, as well as equipment and backpack weight, also play an important, but often neglected role. These factors primarily affect movement economy and thus climbing performance.

19.1 Determinants of Endurance Capacity

19.1.1 Maximal Oxygen Uptake ($\dot{V}O_2$max)

$\dot{V}O_2$max, as a measure of aerobic capacity, expresses in a single value the complex mechanisms involved. These include: Oxygen transfer from air to blood (lungs); its transport within the body (heart, blood), and finally oxygen utilisation in the mitochondria (muscle) for energy production in the form of adenosine triphosphate (ATP). $\dot{V}O_2$max is determined by genetic factors, but can be influenced by training within this framework. The oxygen transport and utilisation systems are illustrated in ◘ Fig. 19.2.

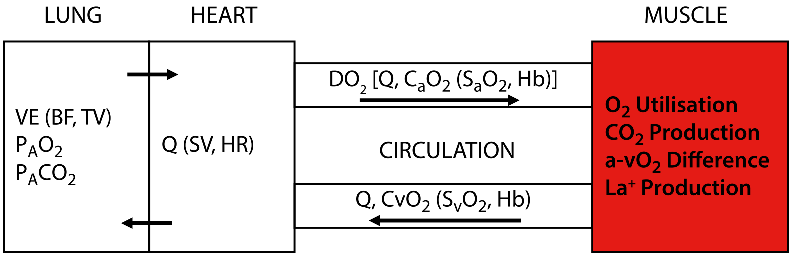
The Fick equation illustrates the relationship between $\dot{V}O_2$max, oxygen transport by the heart and blood, and muscular oxygen utilisation (Q = cardiac output [heart rate × stroke volume], 1.34 = Hüfner number, [Hb] = haemoglobin concentration, S_aO_2 = arterial oxygen saturation, S_vO_2 = Oxygen saturation of mixed venous blood in the right atrium):

$$\dot{V}O_2\,\max = Q \times [Hb] \times 1.34 \times \left(S_aO_2 - S_vO_2\right)$$

The partial pressure of oxygen decreases in a cascade from ambient air to the mitochondria of the working muscles. There are three key points (◘ Fig. 19.3) at which altitude has varying effects.

▪ Atmosphere—Alveoli

The most pronounced altitude-dependent change is due to altered environmental conditions, as the decreasing barometric pressure leads to a proportional reduction in the partial pressure of oxygen. At 5500 m, it is only about half as high as at sea level. Thus, the starting level is significantly reduced. After inspiration, the body-warmed water vapour saturation further unavoidably reduces the partial pressure of oxygen on its way to the alveoli. In the alveoli, the partial pressure of oxygen (p_AO_2) is further decreased by metabolic carbon dioxide from the blood. The magnitude of this reduction, for a given carbon dioxide production, is a function of ventilation. This explains the powerful effect of hyperventilation (more carbon dioxide is exhaled) for acclimatisation at altitude, as increasing ventilation can approximately halve the altitude-induced reduction in p_AO_2 from inspiratory conditions to alveolar levels, even at rest. This effect is more pronounced during exercise.



◘ **Fig. 19.2** Oxygen transport from the lungs to the mitochondria in working muscles. $\dot{V}E$ minute ventilation, *RR* respiratory rate, TV tidal volume, p_AO_2 and p_ACO_2 partial pressure of oxygen and carbon dioxide in the alveoli, *Q* cardiac output, *SV* stroke volume, *HR* heart rate, DO_2 oxygen delivery, C_aO_2 arterial oxygen content, S_aO_2 arterial oxygen saturation (in the pulmonary capillaries), *Hb* haemoglobin concentration, *a-v*O_2 arteriovenous oxygen difference, La^+ lactate concentration, S_vO_2 mixed venous oxygen saturation, C_vO_2 mixed venous oxygen content, VO_2max maximal oxygen uptake. (Burtscher 2013)

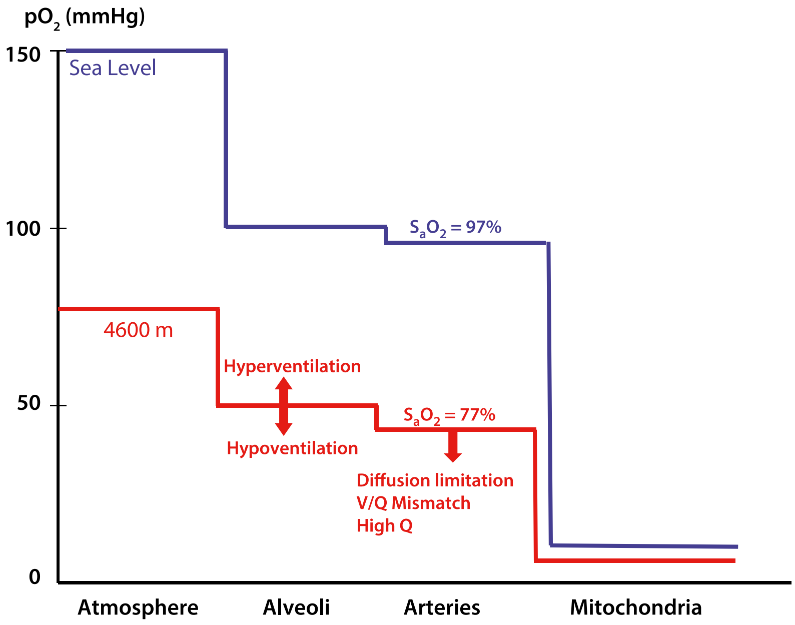


Fig. 19.3 Oxygen cascade during light exercise at low altitude and at approximately 4600 m. *pO_2* partial pressure of oxygen, *S_aO_2* arterial oxygen saturation, *V/Q* ventilation/perfusion, *Q* cardiac output. (Burtscher 2013)

> Hyperventilation is a powerful compensatory mechanism countering the oxygen deficiency; the individually variable expression of the hypoxic ventilatory reflex can be tested in the laboratory.

Alveoli—Pulmonary Capillaries—Arterial Blood

The level of p_AO_2 is crucial, as it is the driving force for oxygen loading of the erythrocytes in the pulmonary capillaries, and higher values generally allow for more efficient loading. In addition, hyperventilation lowers p_ACO_2 and CO_2 in the blood, which increases the binding affinity of haemoglobin for oxygen, further improving oxygen loading.

Mechanistically, the reduced arterial oxygen partial pressure (p_aO_2) or the lower S_aO_2 immediate triggers hyperventilation via peripheral chemoreceptors (especially in the carotid bodies at the bifurcation of the carotid artery). This is the hypoxic ventilatory response. An inadequate ventilatory response to hypoxia during exercise leads to a cascade of a reduced p_AO_2, reduced S_aO_2, and ultimately a reduced aerobic capacity (Burtscher et al. 2006).

In the lungs, hypoxia induces vasoconstriction of the pulmonary vessels (Naeije et al. 2010). This immediate, so-called Euler-Liljestrand reflex aims to optimise gas exchange in the lungs by perfusing alveoli with lower oxygen concentrations less than those with higher concentrations of oxygen. However, at altitude, especially during additional physical exertion, this reflex can contribute to pulmonary hypertension (increased blood pressure in the pulmonary circulation) (Dehnert et al. 2005). Pulmonary hypertension can, by increasing right ventricular afterload, lead to a reduction in cardiac output (Q), a pathological ventilation-perfusion ratio, and injury to the alveolo-capillary membrane with subsequent oedema formation—all promoting a reduction in pulmonary oxygen diffusing capacity. This, in turn, results in a decrease

◘ **Table 19.1** Exercise test results of a very successful high-altitude mountaineer at low altitude (600 m) and in simulated altitude of 5000 m (Burtscher et al. 2009)

	Altitude: 600 m	Altitude: 5000 m
$\dot{V}O_2max$ (ml/kg/min)	65	49
85% $\dot{V}O_2max$ (ml/kg/min)	55	42
$\dot{V}Emax$ (l/min)	133	170
$\dot{V}E$ at 85% $\dot{V}O_2max$ (l/min)	85	111
$\dot{V}E$/MVV at 85% $\dot{V}O_2max$ (%)	40	52

in p_aO_2 and S_aO_2, thereby reducing aerobic exercise capacity (Calbet et al. 2003a, b; Naeije et al. 2010). Diffusing capacity, i.e. gas exchange between the alveoli and arterial blood across the capillary diffusion membrane, can be a limiting factor for performance at altitude even in healthy individuals. Some data suggest that well-trained mountaineers possess a higher pulmonary diffusing capacity than equally trained non-mountaineers (Puthon et al. 2016; Burtscher et al. 2009; Burtscher 2013; ◘ Table 19.1) and that pulmonary diffusing capacity improves during the first weeks of altitude exposure (Agostoni et al. 2011).

Maximal oxygen uptake ($\dot{V}O_2max$), maximal minute ventilation ($\dot{V}Emax$), and minute ventilation at 85% of $\dot{V}O_2max$ (= assumed threshold for sustained performance).

■ Cardiovascular System

At altitude, and especially at extreme altitudes above 5500 m, Q during submaximal exercise intensity increases, while maximal Q decreases (Calbet et al. 2003a, b). The main factor responsible for the increase in submaximal Q at altitude, which leads to an improved O_2 delivery, is the enhanced sympathetic activity and the resulting increase in heart rate. The reduction in Q during maximal exercise appears to be primarily due to the altitude-induced reduction in plasma volume and the resultant decrease in cardiac stroke volume. This begins about one day after ascent (Siebenmann et al. 2013). Other contributing factors include altitude- and exercise-induced pulmonary hypertension and a reduction in maximal heart rate. The latter may be due to hypoxia-induced inhibition; however, the evidence is mixed (Mourot 2018) and does not fully account for changes in autonomic regulation that occur over the course of acclimatisation to altitude (Siebenmann et al. 2017).

The submaximal increase in cardiac output leads to a reduction in the contact time between oxygen in the alveoli and the oxygen carriers (erythrocytes); thus, complete oxygen saturation is no longer achieved. This mechanism, in addition to those already mentioned, further influences individual diffusing capacity and becomes particularly relevant at extreme altitudes. Consequently, a high cardiac output in high-altitude mountaineers can only be effectively utilised if a correspondingly high pulmonary diffusing capacity allows for rapid oxygen loading of the pulmonary capillary blood (Burtscher 2013).

■ Arterial Blood—Cell (Mitochondria)

A decrease in S_aO_2 is associated with a reduction in the oxygen concentration gradient between capillary blood and mitochondria in muscle cells, resulting in a diminished aerobic energy supply. Of course, factors such as the capillarisation of the working musculature, which depends on training status, fibre type distribution, myoglobin concentration, and mitochondrial density and function, play a decisive role in the utilisation capacity of available oxygen. However, oxygen extraction capacity does not appear to be a limiting factor for $\dot{V}O_2$max at altitude (Calbet et al. 2003a, b).

In summary, in contrast to low altitude, at high altitude the alveolar-arterial oxygen diffusion becomes the limiting factor during submaximal endurance activities such as mountaineering and can only be partially compensated by an increase in respiratory and cardiovascular function (Naeije et al. 2010; Burtscher et al. 2009).

Figure 19.4 illustrates why low capacities in one subsystem (e.g. gas exchange in the lung) cannot be compensated for by high capacities in another subsystem.

In contrast to low altitude, at high altitude even in healthy individuals, gas exchange in the lung becomes performance-limiting during exercise that involves large muscle groups (e.g. mountaineering).

Determination of VO_2max and Assessment of Performance Capacity at Altitude

$\dot{V}O_2$ max can be determined relatively easily by spiroergometry in the laboratory or, with somewhat greater effort, in the field. Although it should not be regarded as an optimal predictor of mountaineering performance, it does allow for a rough estimation of altitude-dependent endurance capacity. In addition, it provides investigators with information on respiratory and cardiovascular responses to exercise. If performed in sufficient time prior to a high-altitude venture (trekking trip or expedition), it can inform on targeted training interventions and subsequently allow for assessment of training success. Figure 19.5 shows the approximate individual $\dot{V}O_2$max required to ascend a given vertical distance per hour at different altitudes, albeit only with light mountain boots, good trail conditions, and light loads. It also illustrates, by way of example, the age-related decline in $\dot{V}O_2$max (approximately 10% per decade) for a well-trained and a less well-trained individual.

While the untrained (but healthy) 40-year-old individual can just manage to ascend 300 vertical metres per hour at 3500 m, this may still be possible, from a cardiopulmonary perspective, even for a well-trained 80-year-old. Greater altitudes, poor trail conditions, cold, and heavy additional loads increase the demands on individual endurance capacity (Burtscher 2004).

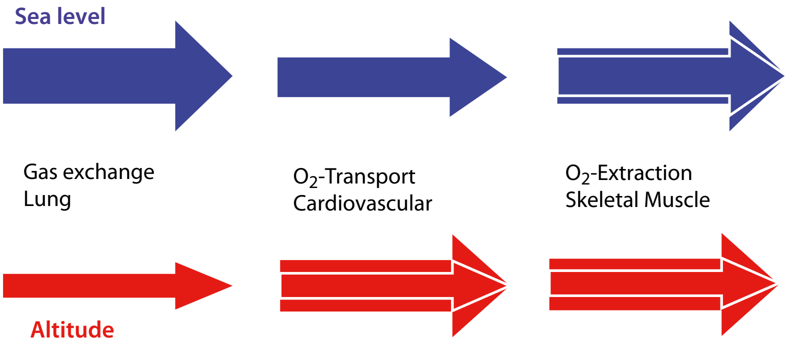


Fig. 19.4 Altitude-dependent significance of alveolar-arterial gas exchange, oxygen transport capacity, and oxygen extraction in healthy individuals. The *thickness of the arrows* represents the respective capacity. The *white arrows* indicate the influence on components downstream of the key components, and thus on $\dot{V}O_2$max

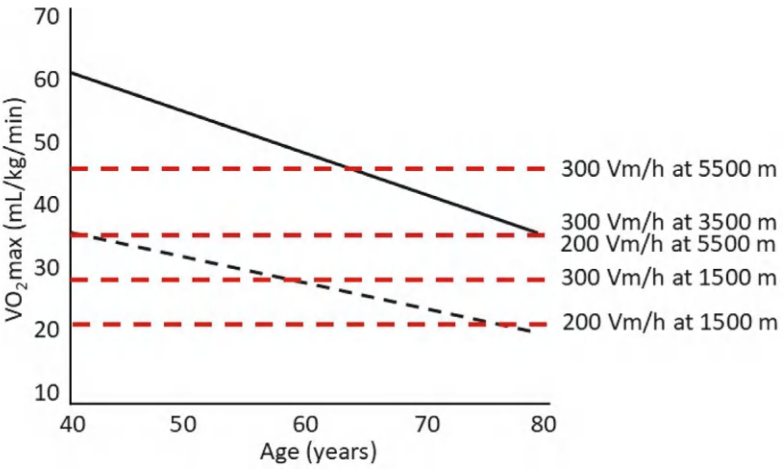


Fig. 19.5 Age-related decline in $\dot{V}O_2$max in a well-trained (*upper line*) and a less well-trained individual (*lower dashed line*). The *dashed red lines* indicate the approximate $\dot{V}O_2$max required to ascend 200 or 300 vertical metres (Vm) per hour (h) at different altitudes (with good trail conditions and light additional loads, e.g. backpack). (Burtscher 2004)

A medical exercise test (spiroergometry) should be performed well in advance (6–12 months) of a high-altitude trek/expedition.

19.1.2 Sustained Performance Threshold (%$\dot{V}O_2$max)

The sustained performance threshold refers to the exercise intensity (as a percentage of $\dot{V}O_2$max) that can just be maintained over a prolonged period (> 1 and up to several hours). Alongside $\dot{V}O_2$max, it is an important parameter of endurance performance ability. Typically, for durations exceeding 1 hour, it ranges between 70 and 80% of individual $\dot{V}O_2$max, but in highly trained endurance athletes, it can exceed 90% (Jones et al. 2021). This threshold can be determined individually through lactate performance diagnostics or spiroergometry, enabling the derivation of personalised training recommendations. It depends on characteristics of the working muscles such as their capillarisation and mitochondrial function along with other factors. The sustained performance threshold can be significantly influenced by training (Burtscher et al. 2008; Burtscher 2013).

The sustained performance threshold is reduced during acute altitude exposure, both in absolute terms and relative to (%$\dot{V}O_2$max at altitude) (Faulhaber et al. 2021). However, similar to $\dot{V}O_2$max, it increases again during acclimatisation (Burtscher et al. 2006) when S_aO_2 rises. This is due not only to the ventilatory acclimatisation described above, but also, among other factors, to haematological acclimatisation. In the short term, this involves a reduction in plasma volume (haemoconcentration), and in the medium term, an increase in haemoglobin mass. As a result, the oxygen supply per unit of blood volume improves, exercise-induced adrenaline concentrations decrease, glycolytic energy production is reduced, and the sustained performance threshold rises again.

19.1.3 Movement Economy

Movement economy is determined by measuring oxygen consumption during a specific submaximal, sport-specific activity, such as a defined running or climbing speed (Burtscher et al. 2008). Considerable individual differences are often observed in mountain sports (Oelz et al. 1986). Constitutional factors and years of adaptation to alpine activities—such as trudging through snow, climbing with crampons, or rock climbing—appear to be important influencing factors. In addition, equipment, trail conditions, and extra load can significantly alter movement economy. On the one hand, movement economy can improve through adaptation to the specific mountain activity. On the other hand, it may be impaired by fatigue and/or illness. It is therefore not surprising that highly trained mountain runners train mostly in the mountains and accumulate over 1000 hours of training per year (Millet and Jornet 2019).

> An individual's experience in alpine movement is essential for safe and efficient locomotion during high-altitude expeditions and influences their endurance capacity.

19.2 Altitude and Cold

Performance during mountain sports in winter (and occasionally in summer) can be further impaired by cold in addition to altitude-induced hypoxia. For example, energy expenditure at altitude is further increased in a colder ambient temperature (Toner and McArdle 1988). Hypoxia can delay the onset of shivering for heat production, thereby promoting cooling and the development of hypothermia (Johnston et al. 1996).

Increased ventilation at altitude, when combined with cold, leads to greater respiratory water loss and may also cause respiratory symptoms (cold- or exercise-induced broncho-constriction). Inhaling cold air through the nose can, in turn, reduce the exercise-induced ventilatory response causing a relative hypoventilation (Burgess and Whitelaw 1988).

It is particularly important to note that, in addition to altitude, cold can contribute to the constriction of the pulmonary vessels, thereby provoking pulmonary hypertension or even the development of pulmonary oedema (Li et al. 2018; Giesbrecht 1995). Pulmonary hypertension, in turn, can lead to a reduction in blood oxygen saturation and thus also in physical performance.

19.3 Significance of Additional Weight

In addition to varying terrain conditions (scree, deep snow, ice, etc.), physical performance in the mountains is significantly influenced by additional loads (boots, backpack, equipment). This becomes particularly noticeable with increasing altitude and the associated decline in performance.

Although modern mountaineering equipment has become considerably lighter, a minimum amount of protective clothing, safety equipment, provisions, etc., remains necessary. For example, if a 70 kg mountaineer ascending with a 7 kg backpack is roughly expending about 10% more energy than without a backpack. They will spend approximately 10% longer doing the ascent. With 14 kg of additional weight, energy consumption and ascent time increase by 20%. Increasing backpack weight can also potentially reduce movement economy, especially if the backpack is not carried symmetrically or close to the body. The comparatively high weight of footwear in high-altitude mountaineering should not be underestimated. Depending on sex and walking speed, the energy cost per kg of shoe weight is about 2–5 times higher than that of 1 kg of additional body weight (Holewijn et al. 1992). Additional weight can significantly impair performance at altitude, especially when individual physical capacity is already relatively low. The effects are relatively greater in lighter individuals.

> Additional weight results in a reduction of absolute physical performance.

19.4 Peak Performance and Limitation at Extreme Altitude

Skyrunning is a young discipline within mountaineering and involves mountain running above 2000 m altitude on technically demanding trails, with the aim of reaching summits in the shortest possible time. General exercise physiology findings for successful skyrunning are currently found mainly in case reports (Burtscher et al. 2009). An exceptionally fit and altitude-adapted mountaineer (41 years, 181 cm, 77 kg) was able to reach the summit of Mount Everest from a base camp and return in a single day. He accomplished this from the advanced base camp at 6300 m on the north route to the summit (8849 m) and back without supplemental oxygen in 16 h and 42 min (Burtscher et al. 2009).

To determine which physiological characteristics enabled him to achieve this extraordinary feat, various sports medical tests were conducted at low altitude and in a simulated altitude of ~5000 m. It was found that his haemoglobin concentration (16 g/dl), vital capacity (5.5 l), $\dot{V}O_2$max of ~65 ml/kg/min, and anaerobic performance (sprint capacity) were not exceptional compared to elite endurance athletes. However, his diffusion capacity and ventilatory capacity (maximal voluntary minute ventilation) were above average (~130% of expected normal values). His $\dot{V}O_2$max was sufficiently high to allow continuous walking (ascent) above 8000 m without supplemental oxygen, despite the altitude-related decline (~10% per 1000 m above 1500 m). With an age-appropriate $\dot{V}O_2$max of, for example, 40 ml/kg/min, this would not have been possible. Furthermore, the actual performance decline at 5000 m (for the mountaineer in ◘ Table 19.1) was only 25% compared to the expected 35%.

The importance of baseline physical capacity ($\dot{V}O_2$max) at low altitude for an ascent of Everest without supplemental oxygen is illustrated in various studies in ◘ Fig. 19.6. The results of a maximal exercise test (spiroergometry) at low altitude (600 m) and in simulated altitude of ~5000 m are shown in ◘ Table 19.1 (Burtscher et al. 2009).

Particularly striking are the efficient cardiovascular and respiratory responses during exertion at 85% $\dot{V}O_2$max of the mountaineer in ◘ Table 19.1. This enables the mountaineer to experience only minimal fatigue even during prolonged exertion at altitude. Similar results were also demonstrated in a classic mountaineering study by Oelz et al., published in 1986 (Oelz et al. 1986). The research group examined, 4 years after the first ascent of Mount Everest without supplemental oxygen in 1978, the two exceptional mountaineers Peter Habeler (41 years) and Reinhold Messner (39 years). Messner had the lowest $\dot{V}O_2$max at 49 ml/kg/min, and Habeler the highest at 66 ml/kg/min relative to body weight. It was shown that the highly successful high-altitude mountaineer Reinhold Messner, with this lower $\dot{V}O_2$ max, was still able to move efficiently on the 35% steep “laboratory terrain”, whereas his somewhat lighter climbing partner required 9–16 ml/min more oxygen per kilogram of body weight. His movement economy was evidently very high. However, it should be noted that certain characteristics (e.g. body mass, training status) may have changed since the Everest ascent. Decades of alpine experience, consistent and extensive sport-specific training, adequate risk assessment skills, low susceptibility to injury, and especially the meticulously planned logistics of preparation (acclimatisation) and execution of the ascents com-

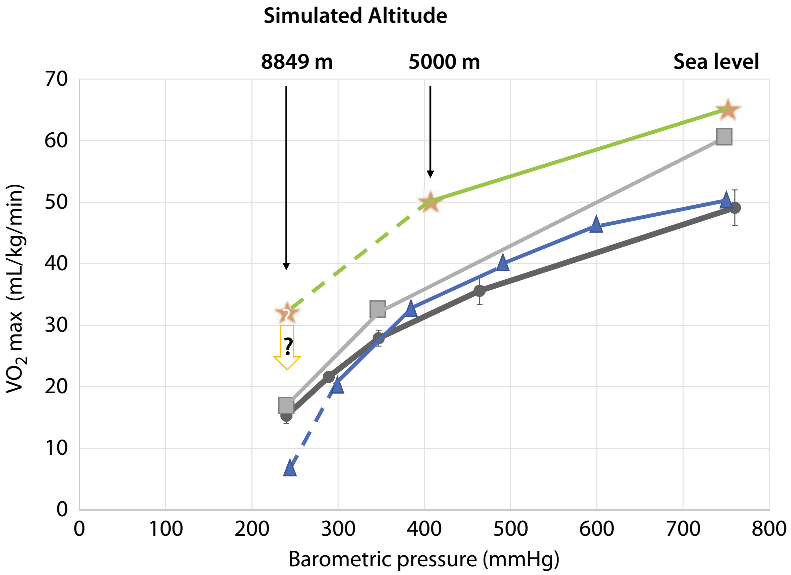


Fig. 19.6 Decrease in maximal oxygen uptake ($\dot{V}O_2$max) from sea level to the (simulated) summit of Everest (8849 m, air pressure: 240 mmHg), measured in the Operation Everest II study (*black circles*) (Cymerman et al. 1989), the Himalayan Scientific and Mountaineering Expedition (measured up to 7440 m and then extrapolated; *blue triangles*) (Pugh et al. 1964), the American Medical Research Expedition to Everest (measured up to 6300 m, ambient air, 16% O_2 and 14% O_2—Everest summit simulated; *grey squares*) (West et al. 1983), and our case observation (measured up to 5000 m in simulated altitude and then extrapolated—2 models; *stars*) (Burtscher et al. 2009). (Modified after Burtscher and Viscor 2022)

plete the profile of successful high-altitude mountaineers and skyrunners.

Conclusion

Individual endurance capacity is a decisive factor for performance in mountaineering. The increasing lack of oxygen with rising altitude leads to a continuous decline in aerobic capacity (~6–10% per 1000 metres of altitude). Alveolar-arterial oxygen exchange plays a significantly greater performance-limiting role at altitude than at sea level and can only be partially compensated by hyperventilation and increased oxygen transport capacity.

In addition to cold, the extra weight from backpack, safety equipment, and boots has a particularly strong impact on performance at altitude. Many years of experience in mountain activities, good training status, and sufficient acclimatisation are basic prerequisites for sustained performance at altitude and are often also essential for the success of high-altitude endeavours.

Health status and performance capacity should be assessed as part of a sports or altitude medical examination at least 6–12 months before a high-altitude activity (trekking, expedition) to identify risk factors and enable targeted preparation. A follow-up examination allows for assessment of training progress.

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20

Altitude Training

Hannes Gatterer and Martin Faulhaber

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Altitude training is primarily used in elite sport to optimise athletic performance. There are a variety of altitude training concepts, but their effectiveness has not been clearly established.

From a scientific perspective, altitude training and its effects on physical performance have attracted increasing interest since the Summer Olympic Games in Mexico City, which took place at an altitude of approximately 2300 m (Meller et al. 1974; Burtscher et al. 1996). It was shown there that "short-distance events" (up to about 1-min duration) benefited particularly from the lower air density at 2300 m, whereas performances in longer events were impaired by the reduced oxygen availability compared to sea level.

While there is little doubt that living and training at altitude improves aerobic performance at altitude, whether altitude training also leads to performance gains at sea level remains scientifically unresolved. As a result, a variety of altitude training approaches have been implemented and studied. These concepts can be broadly divided into:

- Continuous altitude or hypoxic exposures.
- Intermittent altitude or hypoxic exposures.

20.1 Continuous Hypoxic Exposures ("Live High—Train High", Traditional Altitude Training)

In this form of altitude training, athletes typically live and train for several weeks at altitudes between 1500 and 2500 m. From a practical perspective, traditional altitude training is generally only feasible at natural altitude, as continuous stays with training in altitude rooms or tents do not appear effective (key issues: isolation, restricted movement).

During altitude acclimatisation, hyperventilation occurs, plasma volume decreases (haemoconcentration), and after at least 2 weeks of exposure, erythropoiesis and muscular "remodelling" are also likely to take place.

These adaptations are beneficial for aerobic performance and thus for endurance competitions at altitude. For preparation for competitions at altitude, a 1- to 3-week altitude training camp at the competition altitude is therefore recommended (Gore et al. 2008). However, it has also been shown that even short-term acclimatisation stays of two nights can have positive effects on endurance performance at altitude (Burtscher et al. 2006). Short-term acclimatisation can therefore be considered as an alternative if longer stays at competition altitude are not possible or desired.

In contrast, the advantage of traditional altitude training compared to a training camp at low altitude for competition performance at sea level is questionable. It is controversially discussed in the scientific literature (Siebenmann and Dempsey 2020; Millet and Brocherie 2020). Although numerous studies have been conducted on this topic, they are difficult to compare due to differences in altitude, duration, training intensity, and the training status of participants. Traditional altitude training is more likely to improve sea-level performance in less well-trained individuals than in elite endurance athletes (◘ Table 20.1) (Burtscher et al. 1996). The key reason for this is likely to be the altitude-induced reduction in absolute training intensity. This is particularly true in elite athletes and leads to a diminished neuromuscular training effect during the altitude exposure and, consequently, to adverse muscular adaptations. Furthermore, the individual responses of athletes to altitude training are decisive in determining whether performance improve-

Table 20.1 Results of the meta-analysis by Bonetti and Hopkins (2009)

Type of altitude training		Elite athletes		Sub-elite athletes	
		Power output	VO_{2max}	Power output	VO_{2max}
Natural altitude	LHTH	Unclear	−1.5(±2.0)%	+0.9 (±3.4)%	+4.3 (±2.6)%
	LHTL	+4.0 (±3.7)%	Unclear	+4.2 (±2.9)%	Unclear
Artificial altitude	LHTL (8–18 h/d)	Unclear	−0.5(±1.4)%	+1.4 (±2.0)%	/

LHTH live high—train high, *LHTL* live high—train low, *VO_{2max}* maximal oxygen uptake (± 90% confidence limit)

ments are achieved upon return to sea level. Achieving optimal competition performance is further complicated by the individually variable course of re-acclimatisation and the associated optimal timing of competition after returning to sea level (Millet et al. 2010). Therefore, from a scientific perspective, there is no conclusive evidence for the effectiveness of this concept in endurance athletes at the highest performance level.

20.2 Intermittent Hypoxic Exposure

Intermittent hypoxia (IH) is defined as repeated exposures to hypoxia, interrupted by periods of normal oxygen availability (Neubauer 2001). In this section, only those forms of IH induced by stays at natural or simulated altitude, or by breathing hypoxic gas mixtures (via mask), applied for the purpose of altitude training, are considered. (In principle, pathological conditions such as IH associated with obstructive sleep apnoea syndrome (OSAS) also fall under this term.) The terminology used in the literature for IH applications is non-specific and does not allow for systematic differentiation between protocols. In general, IH protocols are characterised by the following parameters:

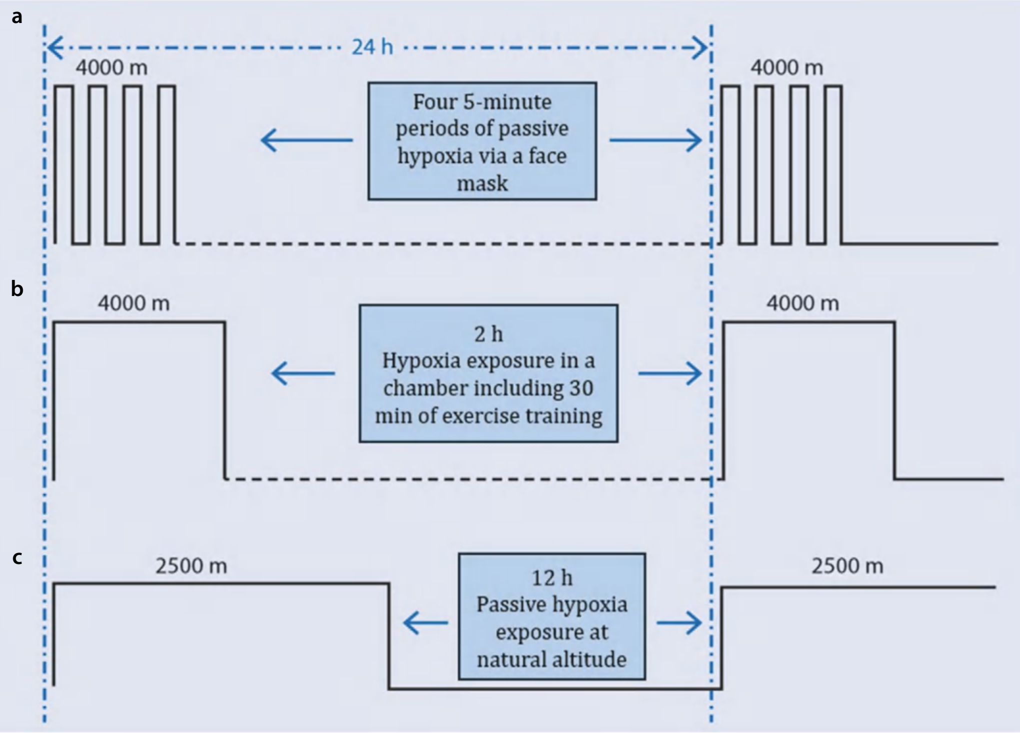
- The severity of hypoxia is usually specified as the inspiratory partial pressure of oxygen in the inhaled air. In hypobaric hypoxia, this depends on the reduction of total atmospheric pressure, while in normobaric hypoxia it depends on the reduction of the inspiratory oxygen fraction (F_iO_2). Although there are physical and physiological differences between hypobaric and normobaric hypoxia, their effects on the organism are a matter of ongoing debate (Millet and Debevec 2020; Richalet 2020). Nevertheless, in practice, for improved comparability and clarity in normobaric hypoxic exposures, the inspiratory oxygen fraction is converted via the partial pressure of oxygen to the corresponding simulated altitude and used as an indicator of intensity. For example, an F_iO_2 of 14% in normobaric hypoxia at sea level corresponds to a simulated altitude of approximately 3200 m.
- The duration of individual hypoxic phases can vary from a few minutes to several hours. In IH protocols with very short hypoxic phases, these are repeated several times per session, whereas hypoxic phases lasting several hours usually occur only once per day. Depending on the area of application, the respective IH protocols are implemented over a period of 1–6 weeks.
- A general distinction is made as to whether exercise training takes place during the hypoxic phases or not. If physical training is performed under

hypoxic conditions, the individual exercise intensity (degree of exertion) also plays a role.

Based on the parameters mentioned, and in accordance with the scientific literature, three main groups of IH protocols can be distinguished (Burtscher 2005; Katayama 2009). ◘ Figure 20.1 schematically illustrates a simplified example from each group.

- *Group A:* IH with 3- to 5-min passive hypoxic cycles at a simulated altitude of 3000–5000 m, interrupted by normoxic phases of approximately equal duration. The cycles are repeated three to five times per session. Over a period of 2–4 weeks, daily applications can be made. Due to the interval-like alternation between hypoxia and normoxia, these protocols are often referred to as "interval hypoxia".
- *Group B:* IH with 1- to 4-h passive or (partially) active hypoxic exposures at an (simulated) altitude of 3000–5000 m. Over a period of 1–5 weeks, daily applications can be made. In practice, protocols in this group are used as "live low—train high" and as "repeated short-term passive hypoxic exposures", which, in a broader sense, are also assigned to the "live high—train low" concept.
- *Group C:* IH with 4- to more than 12-h passive hypoxic exposures at an (simulated) altitude of 2000–3000 m (or higher). Application over several weeks occurs on individual days up to daily. The altitude training concept "live high—train low" falls into this category.

The choice of IH protocol is determined by the type of adaptation wished for. Protocols from Group A and, in part, from Group B


a
24 h
4000 m
Four 5-minute periods of passive hypoxia via a face mask
4000 m
b
4000 m
2 h Hypoxia exposure in a chamber including 30 min of exercise training
4000 m
c
2500 m
12 h Passive hypoxia exposure at natural altitude
2500 m

◘ **Fig. 20.1** Selected examples of intermittent hypoxia protocols from the three groups (A, B, C). (Adapted from Burtscher 2005 and Katayama 2009) (passive exposure) primarily target ventilatory adaptations and adaptations of the autonomic nervous system (Serebrovskaya 2002). Protocols from Group B that include physical exercise ("live low—train high") mainly lead to muscular and neuropsychological adaptations (Hoppeler et al. 2008). IH applications from Groups B and C may equally influence movement economy, whereas only protocols from Group C can result in an increase in erythrocyte count and, consequently, an increase in oxygen transport capacity (Levine and Stray-Gundersen 1997; Siebenmann et al. 2012).

20.2.1 Interval Hypoxia

In this form of intermittent hypoxia, the short hypoxic cycles are usually administered by breathing a hypoxic gas mixture through a mask. As a result, interval hypoxia is almost exclusively applied under artificial altitude conditions.

Interval hypoxia with short hypoxic cycles improves exercise tolerance in older individuals and patients. Although there is sometimes an increase in total haemoglobin mass (Burtscher et al. 2004, 2009), performance-enhancing effects have not been demonstrated in well-trained to highly trained individuals (Julian et al. 2004). Interval hypoxia applications (as defined here) therefore do not appear to be suitable for enhancing physical performance at sea level in athletes. The extent to which interval hypoxia affects performance at altitude cannot be assessed based on the available scientific studies.

20.2.2 "Live Low—Train High"

The core idea of "live low—train high" is to deliberately exploit additional training stimuli by exercising under hypoxic conditions, while recovery takes place under normoxic conditions. Often, only a portion of the training sessions is conducted in hypoxia. Training in hypoxia can, in principle, be performed either in natural or simulated altitude conditions, with the latter usually being preferred for logistical reasons.

A wide variety of protocols are used both in practice and in scientific studies. The duration of interventions ranges from 10 days to 8 weeks, and training intensity varies between 50% and 80% of VO_2max at altitudes of between 2300 and 5700 m. This type of training can induce neuropsychological and muscular adaptations (Hoppeler et al. 2008). The former can be regarded as "acclimatisation" to the altitude-specific sensation of exertion, possibly with reduced central nervous inhibition. The muscular adaptations involve an increase in myoglobin concentration, muscular buffering capacity, and enhanced muscular glucose uptake and utilisation. In contrast, enzymes of aerobic metabolism and muscular capillarisation appear to be no more favourably influenced by hypoxic training than by training under normoxic conditions. A significant disadvantage of hypoxic training is undoubtedly the necessary reduction in absolute training intensity, which may lead to a decline in training quality in the neuromuscular domain.

Improvement in sea-level performance of such training studies is highly inconsistent. A clear advantage over training at sea level has not been demonstrated in endurance athletes. For this reason, this original form of "live low—train high" has somewhat receded into the background. However, there is evidence that "live low—train high" can be used effectively to prepare for training camps or competitions at altitude (Vogt and Hoppeler 2010).

In recent years, a specific form of this training concept has increasingly come into scientific focus. To address the problem of reduced training intensity, repeated (5–10 repetitions, 3–5 sets) short (< 10 s) maximal sprints attempts are performed during hypoxia. With this so-called repeated sprint training in hypoxia, the muscular stimulus (i.e. sprint speed or cycling power) can be maintained at nearly the same level as at sea level, while also providing a hypoxic stimulus. This training has proven effective in increasing resistance to fatigue during repeated sprints, as well as improving aerobic endurance performance (Brocherie et al. 2017; Faiss et al. 2013b; Gatterer et al. 2014). However, the effectiveness of this training for improving sea-level performance remains controversial (Montero and Lundby 2017). As with the original "live low—train high", the performance improvements appear to be due to increased glycolytic activity (anaerobic metabolism) and altered pH regulation (Faiss et al. 2013a). In addition, increased muscular blood flow during exercise (Faiss et al. 2013b) and changes in exercise or pain tolerance have been demonstrated (Álvarez-Herms et al. 2016). Repeated sprint training in hypoxia could therefore be a promising method for achieving performance improvements in sports with an intermittent exercise profile (football, tennis, etc.).

20.2.3 "Live High—Train Low"

Based on the assumption that the reduced absolute training intensity at altitude is a major weakness of classical altitude training, the "live high—train low" concept was developed. The aim of this concept is to harness the effects of altitude exposure (primarily an increase in total haemoglobin mass) and combine them with the maximal absolute training intensities possible at sea level, which appear to be a necessary prerequisite for improving sport-specific performance (Levine and Stray-Gundersen 1997). In practice, both natural and simulated altitude exposures are used for "live high—train low".

The available studies also show heterogeneity with regard to altitude, duration of exposure, and training status of the athletes. Accordingly, the results are inconsistent, with some studies demonstrating an increase in total haemoglobin mass and/or sea-level performance, and others showing no advantage of "live high—train low" compared to a comparable stay and training at sea level. It is generally reported that a minimum altitude of 2000 m with a daily exposure of at least 14 hours over a period of 3 weeks or more is necessary to increase total haemoglobin mass (Rusko et al. 2004). Therefore, "repeated passive short-term hypoxic exposures" in athletes are likely too brief to induce an increase in total haemoglobin mass (Gore et al. 2006). In athletes who respond to the stimulus of an altitude training camp, following the "live high—train low" model (the so-called responders) can increase their total haemoglobin mass by 3–5% (up to 10%) after 300–400 h of altitude exposure (Gore et al. 2013). This is accompanied by a corresponding increase in VO_2max of approximately 3 ml/min/kg per g/kg increase in total haemoglobin mass (Wehrlin et al. 2006; Schmidt and Prommer 2008). However, several studies have failed to demonstrate benefits of this concept, and particularly recent, well-controlled studies have again questioned the erythropoietic effects in elite athletes (Lundby et al. 2012; Robach et al. 2006; Siebenmann et al. 2012). The initial total haemoglobin mass at the start of such an intervention is likely a critical variable. Athletes who already have a high total haemoglobin mass should therefore experience a smaller adaptation (Robach and Lundby 2012), although the literature is inconsistent on this point as well (Hauser et al. 2017). With regard to performance enhancement, a meta-analysis published in 2009 showed that both elite athletes and those at lower levels of performance can improve their performance by approximately 1–4% through this form of altitude training, while changes in VO_2 max remain inconclusive (◘ Table 20.1) (Bonetti and Hopkins 2009). However, these performance-enhancing effects, like the erythropoietic effects, should also be questioned in elite athletes according to more recent studies (Robach et al. 2006; Siebenmann et al. 2012). It is also important to always consider possible placebo, nocebo, or training camp effects (Bonetti and Hopkins 2009).

Another approach to improving endurance performance at sea level is based on optimising movement economy. An improvement in movement economy (e.g. running economy) leads to a lower oxygen consumption at the same movement speed and can therefore result in enhanced performance independently of an increase in maximal oxygen uptake and/or the lactate threshold. Especially in long-distance running events, economy represents an independent determinant of competition performance (Coyle 2007). It has been shown that "live high—train low" improves the running economy of elite runners by approximately 3% (Saunders et al. 2004), and studies have also reported positive effects for "repeated passive short-term hypoxic exposures" (Katayama et al. 2004; Burtscher et al. 2010). However, the results are far from consistent, and several studies have failed to confirm these effects (Truijens et al. 2008; Siebenmann et al. 2012). A key reason for the divergent findings is likely to be that changes in running economy are also strongly influenced by accompanying training stimuli, such as plyometric training or high-intensity interval training (Foster and Lucia 2007). Repeated applications in different training periods have shown that improvements in running economy were achieved only during the preparatory period (with predominantly non-specific training content of moderate intensity) (Burtscher et al. 2010).

Despite ongoing controversies (Siebenmann and Dempsey 2020; Millet and Brocherie 2020), LHTL is still considered the gold standard training concept for improving sea-level performance through altitude training. In 2023, a scientific summary of 25 years of LHTL experience was published (Girard et al. 2023). Ten key lessons were derived. These are:

1. There is a narrow window for the "optimal dose" of altitude (2000–2500 m, 12–14 h of altitude exposure per day, > 2 weeks).
2. There is considerable individual variability in responses, and the mechanisms behind responders versus non-responders to LHTL remain unclear.
3. Iron deficiency impairs the erythropoietic response to altitude, making screening of athletes' iron status prior to commencing an LHTL camp an absolute necessity.
4. If performance enhancement is the primary goal, training load (volume and intensity) must be monitored and appropriately adjusted before, during, and after the LHTL intervention.
5. Successful implementation of LHTL training requires careful monitoring of sleep quality, fatigue status, and hydration status. Infections, illness, or overuse conditions should be avoided.
6. Both the training/competition phase prior to altitude training and the timing of a potential competition or performance assessment after altitude training influence LHTL outcomes.
7. Similar effects on red blood cell mass and maximal aerobic performance can be expected in both natural and simulated altitude.
8. Physiological adaptations (e.g. total Hb mass) following LHTL are often more robust/reproducible than changes in performance.
9. Although endurance athletes (e.g. swimmers, runners, cyclists) are the main target group for the LHTL training concept, LHTL has now also become popular in other sports (e.g. team and racket sports).
10. Additional hypoxic and/or heat exposure (if well controlled) can enhance the benefits of LHTL.

It is also worth noting that hybrid forms have now been developed. One example is the “live high—train low and high” concept (LHTLH), which combines training sessions at altitude (moderate intensity) with sessions at sea level (high intensity) (Millet et al. 2010).

For improving endurance performance at altitude, “live high—train low” appears to be effective in highly trained endurance athletes (Schuler et al. 2007). Thus, “live high—train low” represents a viable option for preparing for competitions at altitude. In contrast, the evidence for “repeated passive short-term hypoxic exposures” in this context is inconsistent. While some studies indicate pre-acclimatisation effects and optimised endurance performance at altitude (Beidleman et al. 2003, 2008), these results have not been supported by placebo-controlled studies (Beidleman et al. 2009; Faulhaber et al. 2010).

Conclusion

Based on the scientific evidence, a general recommendation for the implementation of altitude training in the training routine cannot be made. An individually tailored approach to altitude training, ideally considering previous altitude training experience, remains essential.

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Mountaineering and Hiking with Pre-existing Internal, Neurological, and Psychiatric Diseases

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21.1 Introduction

Hiking and mountaineering, despite their residual risk of accidents, are overall considered to be very beneficial preventive physical activities (Dibben et al. 2023; Pelliccia et al. 2021). However, staying in the mountains can pose a problem for certain individuals with pre-existing diseases. This chapter therefore addresses specific typical internal medical, neurological, and psychiatric conditions in which exposure to moderate and high altitudes may either present a health risk or require special precautions to ensure a safe stay at altitude.

The following aspects are essential for medical advice and clearance:

- The type of pre-existing disease and its potential negative impact on acclimatisation and thus the risk of developing altitude illness: cardiovascular diseases, pulmonary diseases, and haematological disorders with difficult-to-correct chronic anaemia are the most relevant internal medical conditions, as they most significantly impair the body's acclimatisation to altitude.
- Is the underlying disease stable and optimally treated?
- The planned type of stay and level of physical exertion: e.g. altitude exposure with cable car ascent and minimal physical activity and the possibility of rapid descent in case of problems, flight to a high-altitude destination, planned intensive physical exertion (e.g. challenging high-altitude mountaineering tour, trekking).
- The intended maximum planned altitude: e.g. European Alps, Andes, Himalayas.
- The risk of deterioration of the underlying condition due to physical exertion at the planned altitude and under the expected external conditions: e.g. heat, cold, dry air, storms, mental stress.
- The availability of medical care in the event of deterioration of the underlying condition on site: e.g. well-developed emergency air rescue system in the holiday country, if the weather does not prevent the flight, or no possibility of timely medical care.
- Possible additional stress during travel such as a stay in several climate zones (e.g. ascent of Kilimanjaro).
- The residual risk the individual is willing to accept.

A major shortcoming of all medical recommendations and guidelines (Cornwell III et al. 2021; Parati et al. 2018; Donegani et al. 2014) for the medical counselling of individuals with pre-existing diseases prior to a stay at high altitude is that they are based primarily on expert opinion and experience, and that there are only a few high-quality clinical studies addressing the individual topics. Such studies are very difficult to conduct.

MacInnis et al. (2013), for example, studied approximately 500 Nepalese pilgrims of the Janai Purnima who aimed to reach Gosainkunda at about 4400 m within a short time (1–2 days) from Dhunche (starting altitude approx. 2000 m), investigating the incidence of acute mountain sickness (AMS) and risk factors for its occurrence. About one third of all participants developed symptoms of AMS; identified risk factors included female sex, age over 35 years, and rapid ascent.

21.2 Influence of Diseases and Long-Term Medication on the Body's Acclimatisation Response to Altitude

The physiological basis of the acclimatisation response to altitude (summarised in the following overview) is discussed in detail in

► Chaps. 3 and 4, as well as the effects of altitude exposure on the heart and lungs by Bärtsch and Gibbs (2007) and in the European and American guidelines on altitude exposure in patients with pre-existing cardiovascular conditions (Parati et al. 2018; Cornwell III et al. 2021).

Effects of Hypobaric Hypoxia on the Systemic and Pulmonary Circulation

1. *Pulmonary vasoconstriction* with pulmonary hypertension—triggers:
   - Increase in minute ventilation with respiratory alkalosis
   - Hypoxia-induced pulmonary vasoconstriction (von Euler-Liljestrand mechanism)

2. Sympathetic activation:[1]
   - Increase in heart rate, cardiac output, and initially myocardial contractility
   - Increase in systemic arterial blood pressure (with prolonged stay, despite initial hypoxia-induced systemic vasodilation), especially during physical exertion in cold conditions
   - Increase in minute ventilation

In addition, the physiological decline in physical performance at altitude must be taken into account (Bärtsch and Gibbs 2007), and can lead to particular problems in patients with heart failure (Agostoni et al. 2000). In healthy individuals, maximal oxygen uptake decreases by approximately 10% per 1000 m above an altitude of 1500 m altitude and is about 25% lower at 4000 m compared to sea level. The expected oxygen saturations at rest in healthy individuals after 1–2 days at altitude due to hypobaric hypoxia are summarised in ◘ Table 21.1.

◘ Table 21.1 Expected oxygen saturations at rest in healthy individuals after 1–2 days at altitude

Altitude (metres)	Oxygen saturation (%)
5500	70–80
4500	75–85
3500	82–88
2500	90–95
1500	93–97

Adapted from Luks and Hackett (2022)

Based on their physiological significance, it is evident that heart and lung diseases can limit stays at altitude, and that drugs used for treatment of these disorders may interfere with acclimatisation responses. This includes all drugs that inhibit the sympathetic nervous system, such as beta-blockers. Other medications that inhibit the renin-angiotensin-aldosterone system (RAAS), such as angiotensin-converting enzyme (ACE) inhibitors or angiotensin receptor blockers, may even have beneficial effects, as the RAAS is involved in the development of hypoxia-induced pulmonary vasoconstriction, or even they are used in the treatment of specific forms of AMS (e.g. calcium channel blockers). For well-controlled patients, changes in therapy are not necessary for short stays at altitude, such as holidays in the Alps. For planned longer stays (e.g. trekking tours), any adjustments should be made several months in advance to allow optimal management of the underlying condition with more altitude-suitable drugs.

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[1] These changes are triggered by chemoreceptors that detect hypoxia. Sympathetic activation at moderate altitudes (up to approximately 3000 m) is only moderate. The slight increase in systemic arterial blood pressure at rest at altitude usually normalises within a few days. In contrast, pulmonary arterial pressure remains elevated. This increase becomes relevant from an altitude of 3000 m but is highly variable between individuals.

The following key questions should therefore be considered before granting clearance for altitude exposure:

- Is a sufficient increase in cardiac output possible?

  For example, problems to be expected in case of known heart failure, coronary artery disease, or valvular diseases.
- Is a sufficient increase in minute ventilation volume possible?

  For example, problems to be expected in case of severe pulmonary disease, neuromuscular disorders (e.g. myasthenia gravis), or severe obesity, as well as impaired chemoreceptor reflex response (e.g. after surgical procedures at the bifurcation of the common carotid artery or after radiotherapy of this area).
- Can the right heart compensate for the increase in pulmonary vascular resistance?

  For example, problems likely in chronic right heart failure and/or pre-existing pulmonary hypertension.
- Is there a risk of serious consequences from hypoxia or of the development of AMS?

  For example, in patients with cyanotic heart defects, severe anaemia, or sickle cell anaemia.
- Is it possible to optimise the pharmacological management of the underlying condition, or is a change in medication advisable before a longer stay at altitude?

It is important to develop a travel plan with the individual, which should include the following points:

- Ensuring an adequate reserve supply of medication, taking into account any necessary storage temperatures
- Preparation of a travel plan, e.g. considering time zone differences for medication administration, defining triggers that may require adjustment of therapy or discontinuation of the stay at altitude
- If necessary, preparation of an acclimatisation plan
- If necessary, checking whether the required medical devices will function under the expected environmental conditions, e.g. blood glucose meter, insulin pump, blood pressure monitor
- Preparation of an emergency plan, provision of appropriate emergency medication, and training of travel companions in emergency management

21.3 Pre-existing Internal Diseases

21.3.1 Cardiac Diseases

Sudden cardiac death is the second most common cause of death in mountain sports, accidents being the most common. As already published by Burtscher et al. (1993) and subsequently confirmed multiple times (Burtscher 2017), men over the age of 35 who are untrained and exposed to unfamiliar physical exertion in the mountains are particularly at risk during the first 1–2 days. The most frequent cause of death or survived sudden cardiac arrest is previously unknown asymptomatic coronary artery disease (CAD). Spending at least one night above 1300 m before commencing physical activity reduces this risk. The aim of the medical assessment is to identify asymptomatic individuals at risk and provide appropriate advice, especially as the average age of active mountain sports participants continues to rise (Luks and Hackett 2022). Cardiovascular risk assessment should be performed in accordance with sports medicine guidelines (Pelliccia et al. 2021) for asymptomatic individuals over 35 years of age prior to engaging in sports (◘ Fig. 21.1).

Required examinations in individuals with known cardiac disease:

- *Stress test*: Assessment of physical performance capacity is essential: even for stays at moderate altitude, it should be at

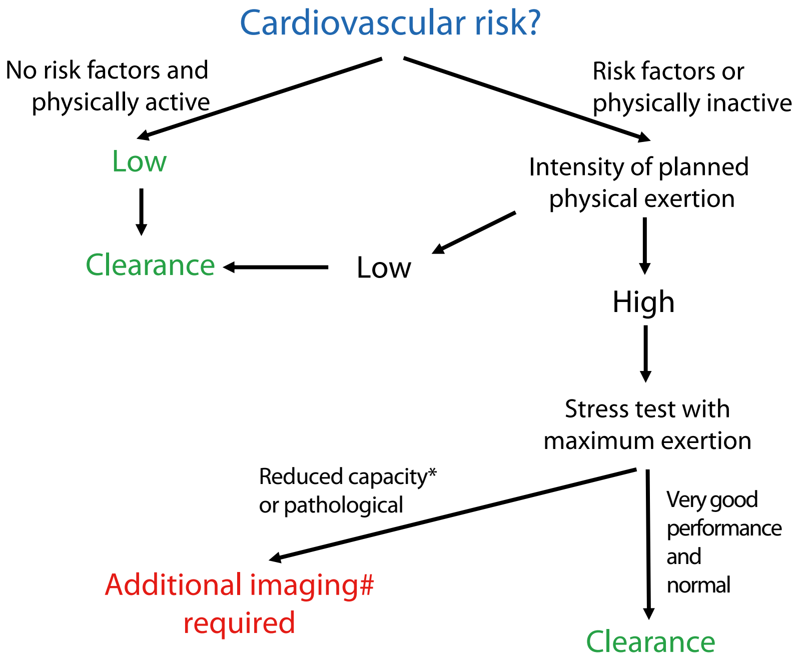

Cardiovascular risk?
No risk factors and physically active
Risk factors or physically inactive
Low
Intensity of planned physical exertion
Clearance
Low
High
Stress test with maximum exertion
Reduced capacity* or pathological
Very good performance and normal
Additional imaging# required
Clearance

Fig. 21.1 Clearance for high-altitude exposure in asymptomatic individuals over 35 years of age without known cardiac disease. (Algorithm modified from Pelliccia et al. 2021). * ≤2 W/kg body weight; # Imaging: morphological (non-invasive coronary computed tomography angiography) or functional (e.g. by myocardial perfusion scintigraphy)

least 2 W/kg body weight to ensure sufficient performance reserve for planned activities. In addition, blood pressure and heart rate responses during and after exertion can be evaluated, and the risk of significant exercise-induced arrhythmias or myocardial ischaemia can be assessed.

- *Echocardiography* (if no recent examination is available): echocardiography is the second basic investigation prior to clearance for mountain sports in individuals with known cardiac disease. It allows assessment of left and right ventricular function and screening for pulmonary hypertension or significant valvular disease.

In individual cases, referral to specialised centres may be appropriate, where cardiopulmonary function testing under normobaric or preferably hypobaric hypoxia can be undertaken (Luks and Hackett 2022). An easily implemented alternative as a provocation test in suitable regions is a stay in a glacier ski area (first stay ≥3000 m) or at a high mountain pass (e.g. Stelvio Pass in South Tyrol, Italy) with the option of rapid descent to the valley if hypoxia-induced problems occur.

21.3.1.1 Arterial Hypertension

Arterial hypertension is the most common incidental finding during routine health and sports medical checks (Pelliccia et al. 2021). Numerous studies have shown that in the first days after exceeding an altitude of approximately 2500 m, arterial blood pressure increases for several days (Luks and Hackett 2022). This rise depends on the altitude reached and is minor at Eastern Alpine elevations (up to 4000 m, systolic <10–15 mmHg), remaining <140/90 mmHg in healthy individuals. However, arterial hypertension may first become evident during a stay at altitude, accompanied by corresponding symptoms. Over the following 4–7 days, arterial blood pressure usually returns slowly to baseline values. Nevertheless, there appears to be a subgroup of individuals in whom blood pressure does not return to baseline at altitude (Wu et al. 2007b). Altitude-associated sleep disturbances and central sleep apnoea are relatively common and can prevent the physiological nocturnal blood pressure dip during sleep (so-called dipping). Prophylactic administration of acetazolamide at high altitudes can, at least in healthy individuals, reduce or even prevent both the altitude-induced rise in blood pressure and central sleep apnoea (Cornwell III et al. 2021).

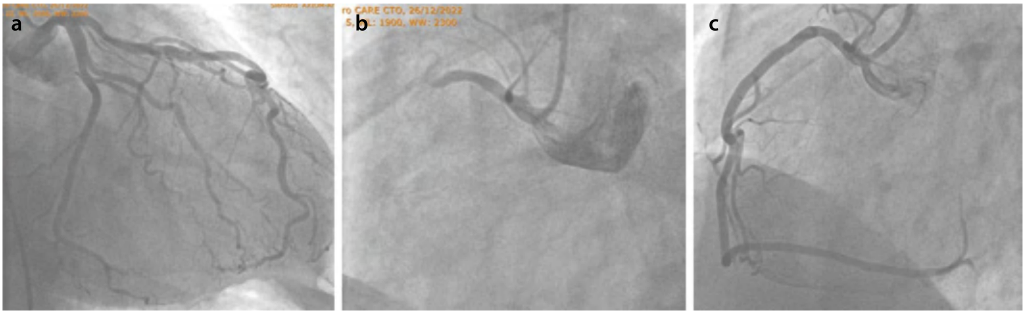
Arterial hypertension must be well controlled under exertion prior to a planned stay at altitude. Optimal blood pressure control during physical activity is defined as values <210/90 mmHg at 100% of the individual age- and sex-adjusted expected standard performance. Before beginning climbing training, resting blood pressure values should be <160/100 mmHg. Due to their tolerability and the physiological changes at altitude, ACE inhibitors, angiotensin receptor blockers, or calcium channel blockers—or a combination of calcium channel blockers with one of these drug classes—are recommended for mountaineers (Parati et al. 2018; Pelliccia et al. 2021). If monotherapy is sufficient, calcium channel blockers are the first choice for frequent stays at high altitude. Well-controlled hypertensive patients without hypertension-induced end-organ damage are considered fit for altitude and there are also no restrictions for competitive sports (Parati et al. 2018; Cornwell III et al. 2021; Pelliccia et al. 2021). It is not necessary to routinely increase medication dosage at altitude. However, for planned, longer stays at altitude, it is advisable to carry a blood pressure monitor to check, in the event of symptoms (e.g. headache), whether blood pressure is involved and to adjust therapy accordingly. A rest period of at least 10 min should be observed before measuring blood pressure. In addition to elevated values, lower blood pressure than usual may also occur due to inadequate fluid intake and prolonged endurance exercise. Patients should be educated in advance regarding appropriate therapy adjustments.

21.3.1.2 Pulmonary Hypertension

In contrast to arterial hypertension, pulmonary hypertension imposes significant limitations on the possibility of staying at altitude, as these patients are particularly at risk due to the increase in pulmonary vascular resistance. Pulmonary hypertension is frequently found secondarily in heart failure as well as in advanced lung diseases, particularly chronic obstructive pulmonary disease (COPD). The increase in pulmonary artery pressure triggered by hypobaric hypoxia can, in cases of severe pulmonary hypertension, leads to right heart failure or the development of high-altitude pulmonary oedema even at moderate altitudes. In principle, severe or already exercise-limiting pulmonary hypertension at low altitude (>NYHA II) or a cyanotic congenital heart defect constitutes a contraindication for stays at altitudes >2000 m. If unavoidable (e.g. air travel), supplemental oxygen should be administered to prevent hypoxia. In patients at high risk of pulmonary hypertension, echocardiography should be performed prior to a stay at altitude to estimate systolic pulmonary artery pressure.

21.3.1.3 Acute Myocardial Infarction

The initial manifestation of CAD as an acute myocardial infarction (AMI) is relatively common and occurs in mountain sports (◘ Fig. 21.2). The exact pathophysiological mechanisms and the temporal triggers of rupture of a coronary atherosclerotic plaque are not yet fully understood. Contributing factors are thought to include



▣ **Fig. 21.2** Acute inferior ST-segment elevation myocardial infarction as the first manifestation of coronary artery disease in a fit recreational athlete during a slope ski tour. This 67-year-old man was a very active and fit amateur athlete (he had successfully completed a half marathon without symptoms approximately two months prior to the event). He had to abandon a ski tour on a slope, which he did not perceive as particularly strenuous, due to nausea. He was still able to ski down to the valley and drive himself home by car. Due to persistent symptoms, emergency medical services were called, and after initial treatment, the patient was transferred for urgent coronary angiography. Apart from a positive family history, there were no cardiovascular risk factors and no recent infection (in particular, SARS-CoV-2 negative at the time of admission) as a possible trigger. The level of physical exertion in this case was only moderate. **a** Left coronary artery with only mild atherosclerotic changes without significant stenoses. **b** Thrombotic occlusion in the proximal right coronary artery. **c** Excellent result after successful primary percutaneous coronary intervention of the right coronary artery

the rise in arterial blood pressure during physical exertion, neurohumoral activation, possible hypercoagulability and platelet activation, or endothelial dysfunction, exacerbated by dehydration during prolonged endurance exercise and recent infections (e.g. “severe acute respiratory syndrome coronavirus type 2”, SARS-CoV-2). However, patients are often above-average in fitness, and the level of physical exertion at which the event occurs is usually only moderate (▣ Fig. 21.2). After excluding existing or recent infections, the search for possible triggers often remains inconclusive, but typically at least one established cardiovascular risk factor is present.

Ventricular fibrillation or sustained ventricular tachycardia caused by AMI or acute myocardial ischaemia is also the most common cause of sudden cardiac death and, under optimal care conditions, of survived sudden cardiac arrest in mountain sports (Burtscher 2017).

A frequent question after AMI, especially in mountainous regions, is when is it safe to resume mountain sports. As the size of the myocardial infarction naturally varies greatly between individuals, no universally applicable recommendations can be made; any ventricular dysfunction and heart failure caused by the AMI must always be considered. Current recommendations (Parati et al. 2018; Cornwell III et al. 2021) do not sufficiently consider cardiac function and are in part not feasible in mountainous regions. For example, even after an uncomplicated acute coronary syndrome or uncomplicated elective stent implantation or bypass surgery, patients are advised to avoid high-altitude stays for at least 6 months (Parati et al. 2018, level of evidence: expert opinion only). In line with sports medicine recommendations (prohibition of competitive sports for 3 months after AMI; Pelliccia et al. 2021), high-intensity endurance sports (e.g. alpine mountaineering) should be avoided for at least 3 months. After AMI, it is advisable to resume alpine sports only after a rehabilitation programme and after assessment of individual left ventricular ejection fraction (LVEF) and exercise capacity, with appropriately tailored recommendations (see section "Stable Coronary Artery Disease"). Depending on the size of the infarction, it is recommended to avoid altitudes >2500 m for 2–6 weeks after AMI and for 2 weeks after elective interventions (in any case, at least 1 week of physical rest is necessary due to vascular puncture of the radial or common femoral artery).

21.3.1.4 Chronic Coronary Syndrome (Formerly Stable Coronary Artery Disease)

Patients with known CAD who are asymptomatic at low altitude usually tolerate moderate altitudes without symptoms; altitudes up to approximately 3500 m are considered low risk. In very physically active individuals, it should be noted that symptoms of significant CAD may be atypical. For example, above-average exercise capacity without angina may still be observed during stress testing, but with a certain decline in performance compared to the previous year, or a so-called walking-through angina pectoris may occur. This means that transient symptoms appear at the beginning of physical activity, but a mountain tour can subsequently be completed as planned without symptoms. Therefore, it is important during stress testing to ensure that individuals are truly exercised to their limit, and testing is not stopped after reaching their age- and sex-predicted norm for time reasons. In patients with known CAD, the main concern during mountain stays is the combination of increased exertion and progressive hypoxia, as well as possibly cold, which can in principle trigger myocardial ischaemia. However, there is only a slight increase in the risk of AMI during physical activity (Mittleman et al. 1993), which is essentially limited to the duration of activity and is significantly lower in trained individuals than in those who are physically inactive. Overall, there is a clear preventive prognostic benefit of physical activity (Biscaglia et al. 2020). However, it should be recommended, especially for men over 35 years of age with or without known CAD, to avoid unusual physical exertion during the first two days of a mountain holiday (Burtscher 2017).

Therefore, the extent of initially possible low-risk activities depends on individual fitness.

If there is clinical suspicion of disease progression in patients with known CAD, functional imaging techniques (e.g. myocardial scintigraphy to assess myocardial perfusion) should be considered to exclude relevant exercise-induced myocardial ischaemia, because the diagnosis of CAD is already established, and the significance of moderate stenoses is usually not assessed in current routine coronary CT angiography.

For stays at altitudes >3000 m in patients with known CAD, the recommendations (Cornwell III et al. 2021; Donegani et al. 2014; Luks and Hackett 2022; Parati et al. 2018) can be summarised as follows:

- Absence of symptoms at low altitude, even during physical exertion.[2]
- Good exercise capacity (>2 W/kg body weight) without evidence of relevant exercise-induced arrhythmias or ischaemia.
- In patients post-myocardial infarction, it should also be noted that with a left ventricular ejection fraction (LVEF) <35%, only altitudes up to approximately 3500 m are recommended.

Asymptomatic CAD patients with normal exercise capacity and cardiac function can participate in mountain sports at Alpine altitudes without restrictions; however, tours in the Western Alps require very good, symptom-free exercise capacity at low altitude. Patients with known CAD should avoid exceptional exertion during the first two days of a mountain holiday, and for acclimatisation, ideally spend one night above 1000 m before starting the planned mountain activities (Burtscher 2017).

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[2] If angina pectoris symptoms occur only during intense physical exertion despite optimised medical therapy, and revascularisation is not possible (e.g. a small vessel side branch or vessel end branch too small for intervention), stays at moderate altitudes are still possible.

It should be noted that CAD patients on single or especially dual antiplatelet therapy have an increased risk of bleeding in the event of injury. Patients must be made aware of this, receive appropriate first aid training, and take suitable wound care materials with them on tour. The same applies to patients requiring oral anticoagulation therapy (e.g. for atrial fibrillation).

21.3.1.5 Heart Failure

The decline in physical performance and increased sympathetic activation with increasing altitude pose risks for patients with heart failure (Agostoni et al. 2000). For this reason, heart failure patients can tolerate passive exposure to moderate altitudes relatively well. However, physical exertion can quickly lead to exhaustion and decompensation, as the decline in exercise capacity with increasing altitude is more pronounced in heart failure than in healthy individuals. Therefore, mountain sports require a stable, optimally treated underlying condition with symptoms only during very intense exertion (New York Heart Association [NYHA] stage I) at low altitude. If symptoms occur during moderate exertion (NYHA II), these activities should be avoided at altitude and altitudes >3000 m in general. An exercise test to determine exercise capacity allows estimation of possible physical activities at altitude. If left ventricular ejection fraction (LVEF) is <35%, stays at altitudes >3500 m are not recommended. In addition, heart failure patients often have further comorbidities, such as CAD, pulmonary hypertension, lung diseases, chronic anaemia, chronic renal failure, or sleep apnoea syndrome, all of which must also be considered when assessing clearance for altitude. Iron deficiency anaemia should be corrected before a stay at altitude. For frequent or prolonged stays at altitude, only β1-selective beta-blockers should be used for heart failure therapy, as carvedilol negatively affects exercise capacity at altitude.

21.3.1.6 Arrhythmias

Exercise under hypoxic conditions can theoretically trigger arrhythmias through sympathetic activation, metabolic changes, or electrolyte shifts due to heavy sweating and respiratory alkalosis. In individuals with healthy hearts, there is no increased risk of relevant ventricular arrhythmias at altitudes of the European Alps (Parati et al. 2018). Unfortunately, there are insufficient data on the incidence of arrhythmias during mountain sports in patients with previously unknown cardiac conditions. However, an increased incidence can be expected during intense physical exertion under hypoxia, although there is currently no evidence of clinical relevance at moderate altitudes. Known additional triggers, such as excessive consumption of alcohol, caffeinated beverages, and similar substances, should be avoided. A maximal exercise test prior to a stay at altitude is indicated for risk assessment, to at least exclude relevant exercise-induced arrhythmias or inadequate rate control in atrial fibrillation at low altitude. Patients with known paroxysmal supraventricular tachycardias who are planning extended stays at altitude in regions with limited medical facilities should be informed about the option of an electrophysiological study and ablation therapy several months before the planned trip.

If even a single ventricular extrasystole is detected in a resting 12-lead ECG during a sports or alpine medical check-up, structural heart disease or potentially familial arrhythmias should be excluded (Pelliccia et al. 2021). Clearance for mountain sports depends on the underlying condition, but moderate-intensity physical activity is almost always possible. Antiarrhythmic medication must be taken continuously, including during mountain sports. Adequate hydration, preferably with isotonic drinks, is essential.

21.3.1.7 Syncope

In addition to cardiac diseases, there are numerous other causes of syncope. The associated loss of consciousness distinguishes syncope from collapse (no loss of consciousness). Until the cause of syncope has been successfully clarified and treated, patients should avoid terrain with a risk of falling. Although the guidelines do not specifically address the issue of resuming mountain sports after a syncope (Donegani et al. 2014; Parati et al. 2018; Cornwell III et al. 2021), the following considerations are relevant:

- In principle, the risk of syncope, including in healthy individuals, is increased within the first 24 h after arrival at altitude probably due to impaired vascular tone regulation from moderate altitude upwards (Falla et al. 2021).
- Did the syncope occur in situations likely to be encountered during mountain sports (e.g. during physical exertion, coughing, micturition)?
- Did the patient sustain any significant injury as a result?
- Was a plausible cause identified, and could it be successfully treated?

However, a clear or reliably treatable cause is often not found. In such cases, terrain with a risk of falling should be avoided for at least 3 months, after which an individual decision should be made together with the patient.

21.3.1.8 Pacemaker

Patients with pacemakers and no structural heart disease are not at increased risk from a stay at altitude (West et al. 2013). During the healing phase, the shoulder and arm on the side of implantation should be rested for at least 3–4 weeks. When programming the pacemaker, it is important to ensure that a dynamic increase in heart rate during exertion is possible, to provide the necessary heart rate reserve under stress. Whether alpine climbing or a via ferrata tour should be categorically prohibited depends on whether the patient has an intrinsic rhythm sufficient for survival. If this is not the case, these sports should be discouraged. Theoretically, pacemaker dysfunction triggered by a fall, for example, due to lead fracture, could result in death even in the absence of severe injury.

21.3.1.9 Implantable Cardioverter-Defibrillator (ICD)

ICD carriers face significant restrictions regarding mountain sports. Depending on the underlying condition, stays at altitude may increase the risk of arrhythmias and ICD discharges. During physical activity, inappropriate shocks due to skeletal muscle potential oversensing are still possible, though much less common than in the past. Terrain with a risk of falling should generally be avoided for at least 6 months. If no ICD interventions are required during this period and the patient demonstrates good exercise capacity in stress testing without relevant arrhythmias, mountain sports in areas without significant risk of falling at moderate altitude may be considered acceptable after informing the patient of the residual risk (individual decision, “shared decision making”). After an appropriate ICD therapy and subsequent therapy optimisation, a further 6-month waiting period must be observed. If an ICD is implanted for primary prophylactic indications, no sport involving the affected arm should be performed in the first 6 weeks after implantation. Terrain with a risk of falling should also be avoided for at least 3 months in these patients, after which an individual decision should be made together with the patient. However, alpine climbing and via ferrata tours are discouraged due to the residual accident risk from an ICD discharge. This risk is lower in an indoor climbing centre or outdoor climbing garden and also when bouldering. Nevertheless, it must be emphasised that, in general, climbing sports pose a risk of lead dysfunction in patients with transvenous pacemakers or ICDs.

21.3.1.10 Acquired Valvular Heart Diseases

The most common acquired primary valvular heart diseases in younger adults are aortic valve stenosis (e.g. early degeneration of a bicuspid aortic valve) and mitral valve regurgitation (e.g. mitral valve prolapse syndrome). In general, valve regurgitations are better tolerated during physical exertion than valve stenoses, which more significantly limit the increase in cardiac output.

Aortic Valve Stenosis

Asymptomatic patients with mild or moderate stenosis tolerate moderate altitudes well. In cases of moderate stenosis, exercise testing is recommended; if exercise capacity is very good and absence of symptoms, altitudes up to approximately 4000 m are possible. However, asymptomatic patients with severe aortic valve stenosis should generally avoid intensive physical exertion. Early surgery or early transcatheter aortic valve replacement implantation is nowadays also recommended for this patient group.

Primary Mitral Valve Regurgitation

As the severity of mitral regurgitation depends on preload and afterload, it may change during physical activity. However, there is no evidence that sport accelerates disease progression. Even asymptomatic patients with severe regurgitation, normal ECG and exercise capacity, high-normal LVEF (>60%), and normal left ventricular size without evidence of pulmonary hypertension may participate in sport without restriction (Parati et al. 2018; Cornwell III et al. 2021; Pelliccia et al. 2021). However, before staying at high altitude, a stress echocardiogram with exercise is recommended to assess systolic pulmonary artery pressure under exertion.

21.3.1.11 Clinical History of Myocarditis

In principle, a break from sport should be taken during all infections, and training should only be resumed after complete recovery, usually after about 2 weeks, depending on the severity and course of the infection. After confirmed myocarditis (e.g. on cardiac magnetic resonance imaging [MRI]), a ban on sport applies for 3 months, and for 6 months for competitive sport, regardless of LVEF (Pelliccia et al. 2021). Long, high-altitude tours in the Western Alps are, in terms of physical exertion, quite comparable to competitive sport. Unrestricted mountain sports are permitted again when ventricular function, resting and Holter-ECG, and exercise testing are all normal. In asymptomatic patients with a complete recovery of all signs of myocarditis on cardiac MRI, an earlier start of sports activities may be possible. However, physical activities should also be restricted for at least 1 month.

21.3.1.12 Patent Foramen Ovale (PFO)

In approximately 25% of all people, the septum primum and septum secundum of the atrial septum do not fuse after birth. This results in a kind of “valve” between the two atria, which, under certain haemodynamic conditions, allows a right-to-left shunt of blood through this temporarily open channel. Due to the increase in pulmonary circulation pressure with increasing altitude, the frequency of such events may in principle rise. Routine screening for PFO before high-altitude exposure is not generally recommended. However, in individuals who have experienced high-altitude pulmonary oedema without an obvious cause, exclusion of a PFO before another high-altitude stay is advisable, as there are reports that a PFO may predispose to high-altitude pulmonary oedema (Röggla et al. 2007). However, there are no data regarding the benefit of prophylactic interventional PFO closure to prevent recurrence of AMS. Prophylactic administration of low-dose acetylsalicylic acid (100 mg/day) during high-altitude exposure is an option to reduce the risk of paradoxical embolism (Kurdziel et al. 2016).

Similar considerations apply to individuals with small, haemodynamically insignificant atrial septal defects and other haemodynamically insignificant right-to-left shunts (e.g. intrapulmonary shunts).

21.3.2 Pulmonary Diseases

The principal problems for patients with pulmonary diseases at altitude are the increase in pulmonary artery pressure and the increased frequency of central sleep apnoea with nocturnal oxygen desaturation. In addition, cold and dry air can particularly worsen exercise-induced asthma symptoms. In patients with chronic obstructive pulmonary disease (COPD), oxygen saturation may decrease more markedly during altitude exposure than in healthy individuals. Nocturnal oxygen desaturation due to central sleep apnoea at altitude must also be considered (Luks and Hackett 2022).

21.3.2.1 Bronchial Asthma

As asthma is a common condition, the question is often asked whether a pre-existing diagnosis of asthma poses a problem for stays at high altitude. It should be noted that bronchial obstruction can be exacerbated by cold, exertion, hypoxia, hypocapnia, and increased ventilation.

All these factors can, in principle, lead to a worsening of bronchial asthma. On the positive side for asthmatics, allergen exposure (such as pollen and house dust mites) is significantly reduced at altitude. In addition, exposure to fine particulate matter also decreases.

Asthmatics can therefore ascend to high and even extreme altitudes, provided they are well educated about their condition. Although studies (Cogo et al. 2004) have shown that asthmatics do not experience an increased rate of exacerbations at altitude, there remains a risk of progressive bronchial obstruction. For this reason, regular peak flow monitoring is recommended, but only with devices using a turbine-based measurement method, as conventional peak flow meters tend to underestimate airflow at higher altitudes or in cold conditions.

Furthermore, patients should be trained in the use of their emergency medication (e.g. inhaled beta-agonists ± short-acting muscarinic antagonists, prednisolone [20–30 mg orally twice daily for a maximum of 5 days]), and, if possible, the administration of supplemental oxygen in emergencies. It is advisable to carry dry powder inhalers containing a combination of inhaled corticosteroid (e.g. beclomethasone, budesonide, fluticasone) and formoterol for both maintenance and demand therapy, as their deposition is not reduced at high altitude, in contrast to pressurised metered-dose inhalers (Luks and Swenson 2007).

21.3.2.2 Chronic Obstructive Pulmonary Disease (COPD)

Patients with COPD generally do not express a desire to ascend to altitudes higher than moderate elevations, especially if this involves physical exertion. These patients are usually aware of their disease-related limitations. Consequently, there are no studies that have specifically addressed this question (Luks and Swenson 2007). Based on studies of fitness to fly, in which the effects of hypoxia at an altitude of 2348 m were investigated, it was found that from a forced expiratory volume in one second (FEV_1) of less than 50% predicted, or a paO_2 of approximately less than 70 mmHg at sea level, there is an increased risk of developing significant hypoxia at this altitude. However, according to this study, it has also been shown that most COPD patients tolerate hypoxia very well and only rarely become symptomatic.

It appears reasonable to advise patients with an FEV_1 below 50% of predicted, or with spirometrically confirmed bronchial collapse, against stays at altitudes above 2500 m if this involves physical activities. A short-term stay without exertion, such as by cable car to the Jungfraujoch, Switzerland, or similar high-altitude tourist destinations, appears acceptable, particularly if a rapid descent is possible. If this is not possible, for example, at high-altitude destinations such as La Paz or Lhasa, such travel should be discouraged, or, if unavoidable, supplemental oxygen should be available during the stay. Portable, battery-operated oxygen concentrators, which can be hired for holidays, are particularly suitable for this purpose (Fischer et al. 2013).

In addition, these patients, like asthmatics, should be trained in the management of exacerbations, i.e. an emergency plan for the use of short-acting bronchodilators, prednisolone (20–30 mg orally twice daily for a maximum of 5 days), antibiotics, and possibly theophylline as a useful backup medication should be taken on the tour (and if possible, additionally supplemental oxygen in case of emergencies). The threshold for initiating emergency medication should be set lower than usual to avoid emergencies at altitude.

21.3.2.3 Interstitial Lung Diseases

Patients with restrictive or interstitial lung diseases are often unable to improve their oxygenation through increased ventilation. Accordingly, these patients are particularly at risk of hypoxaemia during stays at high altitude (Luks and Swenson 2007). Altitudes above 2500 m are unsuitable, especially in the presence of significant diffusion impairment. If such exposure is unavoidable, oxygen must be available during the journey, for example, in portable oxygen concentrators with additional batteries.

21.3.3 Anaemia

Any reduction in the haemoglobin content of the blood decreases the amount of oxygen available in the circulation. Accordingly, in patients with pronounced anaemia, there is an increased risk of hypoxia-induced symptoms (e.g. angina pectoris, symptoms of cerebral hypoxia) even at moderate and especially at high altitudes. Anaemia should be treated as effectively as possible before exposure to altitude (e.g. addressing the source of bleeding, correcting of iron or folic acid deficiency, administration of erythropoietin in chronic renal failure). In the case of sickle cell anaemia, which is rare in Central Europe, it should be noted that stays at altitudes above 2500 m may increase the risk of a haemolytic crisis (Luks and Hackett 2022). In chronic haematological disorders, pharmacological correction of anaemia is often only partially possible; a minimum haematocrit of at least 20% is recommended even for passive stays at altitude. If travel cannot be avoided despite falling below this threshold, prophylactic blood transfusion may need to be considered. It should also be remembered that even healthy individuals require adequate iron stores to develop polycythaemia at altitude. This is particularly relevant for premenopausal women, and prophylactic iron supplementation may be necessary prior to altitude exposure.

21.3.4 Clinical History of Thrombosis or Pulmonary Embolism

Within 3 months of a thromboembolic event, stays at high altitude are not recommended (Luks and Hackett 2022). Patients are usually managed with direct oral anticoagulant therapy. Regular coagulation monitoring is not required with this therapy, and changes in diet do not affect the therapeutic effect. Ongoing therapy should be continued unchanged during the stay at altitude. If the event occurred longer ago and oral anticoagulation has already been discontinued, it does not need to be restarted for altitude exposure, as there is no clear evidence of an increased risk of thrombosis at altitude (Treml et al. 2022), particularly for altitudes below 4000 m. However, adequate fluid intake must be ensured.

21.3.5 Obesity

Patients with an elevated body mass index (BMI >25) have an increased risk of developing AMS (Wu et al. 2007b). In severely obese patients, the necessary increase in minute ventilation at altitude is impaired, and sleep apnoea syndrome, which worsens under hypoxic conditions, is often present as well. Arterial hypertension or diabetes mellitus also frequently occurs in this patient group. In summary, all comorbidities must be considered before approving altitude exposure in these patients; however, the benefits of mountain holidays at moderate altitudes have been demonstrated for patients with metabolic syndrome (Schobersberger et al. 2003; Mair et al. 2008).

21.3.6 Diabetes Mellitus

The significant advances in the management of patients with diabetes mellitus now enable them to lead a normal life and to participate in competitive sports, and even successful extreme mountaineering, such as the ascent of Mount Everest, by individuals with type 1 diabetes has been reported (Hillebrandt et al. 2023; Koufakis et al. 2022). In general, physically active individuals with type 1 diabetes are usually highly skilled in managing their condition and typically have no secondary complications. In contrast, for patients with type 2 diabetes, the causes and consequences of the disease must be considered carefully before approving altitude exposure.

The glucose metabolism disorder itself does not impair acclimatisation to altitude or physical performance. It cannot be reliably predicted whether insulin requirements will increase or decrease with rising altitude and/or physical exertion. Available data vary considerably, particularly due to differences in ascent profiles and physical activity. Prophylactic therapy with dexamethasone is not recommended for diabetic patients undertaking expedition mountaineering (Hillebrandt et al. 2023).

For patients with type 1 diabetes mellitus, several practical considerations are important:

- Daily caloric requirements may vary depending on the ascent route.
- Insulin requirements fluctuate according to physical exertion and food intake (risk of ketoacidosis in type 1 diabetics).
- Cold and hypoxia can affect insulin pumps and blood glucose monitoring systems. An emergency plan must be in place in case of failure of the insulin pump or blood glucose monitoring devices.

Therefore, individuals with type 1 diabetes must be optimally trained before engaging in advanced mountain sport activities. The use of short-acting insulins is preferable, with attention paid to the permitted storage temperature of the insulin, and an adequate supply of replacement insulin must be taken on the tour. The use of insulin pumps is viewed critically, at least in studies on the airworthiness for pilots: pressure differences can cause bubbles to form in the pumps, which may trigger hypoglycaemia due to the rapid release of excessive insulin. Nevertheless, successful ascents of the Aconcagua (6960 m) have been achieved with these systems when appropriate precautions are observed (Hillebrandt et al. 2023). For blood glucose measurement, devices using the glucose dehydrogenase method are recommended, as these appear to provide more reliable results at altitude. Continuous glucose sensors seem to be somewhat less accurate in high altitude and cold conditions but can still be used for blood glucose management (Pavela et al. 2018). In any case, it is advisable for patients with diabetes mellitus to tolerate hyperglycaemia rather than hypoglycaemia during their stay at altitude; blood glucose levels should, therefore, be maintained at the upper end of the desired range (e.g. by reducing or even pausing oral antidiabetic agents). It should be noted that acetazolamide increases the risk of ketoacidosis and should therefore not be taken prophylactically (Hillebrandt et al. 2023). It can be difficult to distinguish the symptoms of hypoglycaemia from those of AMS. For the rapid treatment of hypoglycaemia, fast-acting sources of glucose and glucagon must always be available. On expeditions where rapid medical assistance is not available, tests for the determination of blood ketone bodies should be available in order to diagnose insulin deficiency more quickly in the event of clinical deterioration. In addition, it is important that companions are informed about possible emergency situations and are trained in their management.

21.3.7 Gastrointestinal Diseases

Exposure to altitude can lead to gastrointestinal problems even at moderate altitude, but especially at high and extreme altitudes. Digestive function is influenced by many factors, such as changes in diet, malabsorption, prophylactic medication, and increased microbial contamination of water and food, with nausea, vomiting, diarrhoea, and gastrointestinal bleeding as possible consequences. During the construction of the railway line from Golmud to Lhasa, it was noted that from an altitude of 3500 m onwards, the incidence of haematemesis, melaena, or haematochezia was about 0.5% (Wu et al. 2007a). In addition, gastrointestinal changes in the form of gastritis or duodenitis were observed (Pawar et al. 2018). Therefore, non-steroidal anti-inflammatory drugs should be used with caution, and if their use is necessary, the additional prophylactic administration of proton pump inhibitors is recommended.

Before a planned prolonged stay at altitude, abdominal hernias should be surgically repaired; this also applies to perianal abscesses or anal fissures. Patients with chronic inflammatory bowel diseases require an emergency plan in the event of an acute exacerbation, even during a stable phase of their illness, and prolonged stays in regions with limited medical care are not recommended.

21.3.8 Liver Diseases

The liver is an organ that has received little attention in altitude research. There are very few epidemiological studies on patients with liver cirrhosis who live permanently at altitude. Individuals with chronic liver diseases may also wish to travel to high altitudes during a stable phase of their illness. The physiological response of the liver to altitude has rarely been studied. Available data describe an increase in hepatic blood flow from 3400 to 5000 m (Luks and Swenson 2015). However, in healthy individuals, there is no increase in liver enzymes, nor are there changes in the cytochrome P450 system or in parameters of hepatic synthetic function.

Patients with advanced liver cirrhosis or hepatic hydrothorax will generally not wish to ascend above moderate altitudes due to their clinical symptoms, especially if this involves physical activity. However, individuals with liver disease may already have cirrhosis, which, in the compensated stage, hardly impairs quality of life. Travel to high altitudes, however, requires careful pre-travel assessment. Every patient with compensated liver cirrhosis should undergo gastroscopy and sonography to evaluate the status of oesophageal varices and to exclude ascites and hydrothorax before a prolonged journey or stay at altitude.

In compensated liver cirrhosis at Child-Pugh Score A stage, the risk of altitude illness is not increased. Particular attention should be paid to patients with hepatopulmonary or portopulmonary syndrome.

Portopulmonary hypertension (PoPH): While the diagnosis of portal hypertension is usually made clinically and sonographically, a right heart catheterisation is required to diagnose PoPH. By definition, PoPH is present when the mean pulmonary arterial pressure (mPAP) at rest is ≥25 mmHg, and there is an increased pulmonary vascular resistance (>240 $\text{dyn} \times \text{s} \times \text{cm}^{-5}$, 3 Wood units) in the presence of portal hypertension. The causes of PoPH include massive vasodilation and shunting of the pulmonary (capillary and precapillary) vessels due to vascular remodelling. This is a mechanism mediated by nitric oxide (NO) (Fritz et al. 2013; Rodriguez-Roisin and Krowka 2008), involving endothelin and upregulated endothelial NO synthases. It has been demonstrated that patients with liver cirrhosis have increased NO levels in exhaled air. The underlying mechanisms of the oxygenation disorder are, on the one hand, vasodilation and, on the other, the formation of right-to-left shunts. The pathogenesis is thought to involve increased shear stress in the pulmonary circulation due to the hyperdynamic circulatory state in liver cirrhosis. Vasoactive substances from the splanchnic region, which are not metabolised by the liver as usual, are also likely to be involved. Therefore, it is assumed that patients with PoPH are at increased risk of developing high-altitude pulmonary oedema and impaired right ventricular function at altitude (Luks and Swenson 2015).

Hepatopulmonary syndrome: Hepatopulmonary syndrome in chronic liver disease is defined as hypoxaemia due to pulmonary microvascular vasodilation in patients with portal hypertension. The exact pathophysiology is unknown, but increased hepatic production or reduced hepatic clearance of vasodilators is suspected. The elevated cardiac output results in hypoxaemia due to hyperperfusion relative to ventilation. Diagnosis is made by pulse oximetry and contrast echocardiography. Affected individuals exhibit reduced exercise capacity, which worsens at altitude due to increased hypoxaemia. In severe cases, a stay at altitude without the possibility of rapid descent is contraindicated. Other risk factors for patients with liver cirrhosis at altitude include:

- Patients with liver cirrhosis usually have chronic anaemia (see ► Sect. 21.3.3) of various origins, resulting in reduced oxygen-carrying capacity and exercise tolerance. There are also several case reports of acute oesophageal variceal bleeding during long-distance flights. There is little literature on this topic in high-altitude mountaineers.
- Due to immunosuppression resulting from liver dysfunction, there is an increased susceptibility to infections, particularly pneumonia, during stays at altitude.
- Hypoalbuminaemia increases the risk of interstitial pulmonary oedema even under normobaric conditions.
- Patients with severe liver disease often also have concomitant renal failure, resulting in delayed drug clearance.

21.3.9 Thyroid Disorders

Thyroid disorders are quite common in the general population, and there is no known direct negative impact on stays at altitude. It is advisable to measure thyroid hormone concentrations before travelling to altitude and to initiate treatment as indicated by the test results.

21.3.10 Chronic Kidney Diseases

Mild to moderate renal impairment is frequently encountered as a comorbidity and usually does not affect clearance for stays at altitude (Luks et al. 2008). However, the combination of dehydration and the use of non-steroidal analgesics should be avoided due to the risk of worsening renal function. Severe chronic renal impairment leads to chronic anaemia despite erythropoietin substitution therapy. Naturally, erythropoiesis cannot be further increased at altitude, and therefore prolonged stays at altitude are not recommended. Moderate altitudes and short stays, even above 3000 m (e.g. cable car trips), are generally tolerated well, provided there are no additional, altitude-limiting, relevant cardiovascular comorbidities or complications of renal failure.

21.3.11 Special Considerations in Individuals with Malignant Tumours

The occurrence of a malignant tumour does not automatically imply that the affected individual is unable to participate in mountain sports within their individually varying limits. Physical activities nowadays also play an established role in the rehabilitation of oncology patients. The possible activities and the altitude limit depend on the underlying disease. Tumour diseases and the associated chemotherapy or radiotherapy, as well as concomitant oral steroid therapy, can significantly impair cardiac and muscular performance, making stress testing and echocardiography essential for assessing individual limits. In patients with lung tumours, lung volume may additionally be reduced by resection to as small as half of the expected vital capacity. This leads to a decrease in hyperventilation capacity and a reduction in the diffusion surface. Once more than one third of the vital capacity is lost, an assessment of fitness is required for altitudes above 2500 m. This can be done either directly by passive transport via cable car to altitudes between 2500 and 3000 m or by inhalation of a hypoxic gas mixture (F_iO_2 0.14–0.15) for at least 30 min. As long as the oxygen saturation remains above 85%, it can be assumed that this altitude is tolerated. For higher altitudes, vital capacity and forced expiratory volume in one second should be at least 60–70% of their predicted values. Additionally, chemotherapy or radiotherapy to the thoracic region can lead to a reduction in diffusion capacity. Values below 70% of the predicted value indicate a relevant impairment that cannot be compensated for by hyperventilation. Travel to altitudes above 2500 m is not recommended in such cases.

Tumour diseases or tumour therapies often result in chronic anaemia with an associated reduction in oxygen transport capacity. Therefore, adequate haemoglobin levels are also important for stays at altitude. However, it is only possible to estimate roughly what constitutes a sufficient level. For altitudes up to 2500 m, an Hb of 10 g/dl should be sufficient; between 2500 and 4000 m, Hb should be 12 g/dl; and for higher altitudes, it is not less than 13 g/dl. The main cause of all forms of AMS is insufficient oxygenation. Therefore, in general, adequate vital capacity, diffusion capacity, and oxygen transport capacity must be ensured.

Patients with cerebral tumours or a history of cranial irradiation are likely to be at increased risk of developing AMS or high-altitude cerebral oedema (Falla et al. 2021). In such cases, imaging prior to travel is recommended to at least exclude the presence of perifocal cerebral oedema. Patients with intracranial space-occupying lesions are advised against staying at high altitudes (Falla et al. 2021). However, in individual cases of benign intracranial lesions (e.g.

meningioma), mountain sports may be possible following expert consultation.

Chemotherapy or long-term corticosteroid therapy can increase the risk of gastritis. As this also applies to prolonged stays at altitude, patients who have undergone chemotherapy or are on oral steroids should take a proton pump inhibitor prophylactically at altitudes above 2500 m. For extended mountain travel abroad, it should also be assessed whether the immune system is compromised due to previous chemotherapy or if the disease itself increases the susceptibility to infections. Therefore, prolonged stays at altitude of patients with higher-dose oral steroid therapy are generally not recommended, as possible cerebral altitude complications (high-altitude cerebral oedema [HACE]) may no longer adequately respond to additional steroid administration. All necessary inactivated or live vaccinations must also be planned and administered accordingly.

21.3.12 Patients After Transplantation

In a stable condition with good organ function, these patients are generally fit for altitude a few months after surgery, once surgery-related restrictions have resolved and provided there is no significant additional damage to other organs. Transplant recipients who are physically active are usually very well trained in monitoring and managing their organ function and immunosuppressive therapy.

Post-transplant patients on a calcineurin inhibitor for immunosuppression have an increased risk of arterial hypertension. The increased susceptibility to infection must be considered, as must the need for appropriate prophylactic measures (e.g. vaccinations). As previously mentioned, in patients on long-term steroid therapy, the additional administration of dexamethasone for the treatment of AMS may be less effective. Nevertheless, there have been successful ascents of Kilimanjaro by stable organ transplant recipients under medical supervision.

There are two published case reports of successfully liver-transplanted patients with positive long-term outcomes among Tibetan residents living at >4000 m (Dou et al. 2010; Jin et al. 2009). A single study investigated whether, following liver transplantation with normal cardiopulmonary function and no residual portopulmonary or hepatopulmonary hypertension, a stay at altitude is safe. No differences were found between 6 liver transplant recipients immunosuppressed with tacrolimus and 15 control subjects in terms of performance, oxygen saturation, incidence of AMS, and summit success during an ascent to 5895 m (Pirenne et al. 2004).

In patients with a history of heart transplantation, it is important to note that the transplanted heart is primarily denervated, lacking sympathetic and parasympathetic nerve supply due to surgery. This results in an elevated resting heart rate, a slower increase in heart rate during exertion, and impaired regulation of coronary blood flow. Nevertheless, heart transplant recipients can achieve high levels of athletic performance. For high-altitude stays, it should be considered that residual pulmonary hypertension from the pre-existing cardiac condition may persist and must be ruled out. Therefore, echocardiography and exercise testing are required prior to a stay at altitude.

21.4 Neurological Symptoms and Pre-existing Neurological Diseases

21.4.1 Headache and Migraine

Headaches are common in the general population and occur more frequently during high-altitude mountaineering. They are also the cardinal symptom of AMS. Therefore, it can be expected that individuals who frequently experience headaches in daily life may also develop them during a stay at altitude, particularly during physical exertion (Falla et al. 2021).

Migraine is also a common disorder, but its diagnosis should be confirmed by a neurologist (see ▶ Chap. 25). Hypoxia can trigger a migraine attack; therefore, every patient with migraine should be informed that their symptoms may worsen at altitude (in terms of both frequency and intensity of headaches). Furthermore, it has been reported that migraines may present differently during altitude exposure. For prolonged stays at altitude, prophylactic medication is advisable if no long-term therapy is in place. An individually proven effective medication and an additional drug for possible prevention (e.g. flunarizine or amitriptyline) should be taken in case of long stays at altitude (e.g. for working) based on the individual neurologist consultation (Angelini et al. 2021). It is likely that patients with migraine have a slightly increased risk of developing AMS. It can be difficult to distinguish between headaches as a symptom of AMS and those due to migraine. In cases of migraine with atypical or prolonged aura, a neurological assessment and, if necessary, further investigations are required prior to a prolonged stay at high altitude (Angelini et al. 2021).

21.4.2 Epileptic Seizure and Epilepsy

Epileptic seizures can, albeit very rarely, also occur at high altitude in patients without known epilepsy or underlying neurological disease, triggered by various factors (e.g. hypoxia, respiratory alkalosis, sleep deprivation, electrolyte disturbances, hypoglycaemia) or their combination, even in the absence of altitude illness. If an underlying neurological disorder is excluded after a single seizure, there is no contraindication to further mountaineering, trekking, or climbing activities, provided that alcohol is avoided and precautions are taken to reduce potential triggers (Angelini et al. 2021; Küpper et al. 2014). However, a waiting period for activities with a risk of falling of 3 months after a provoked and 6 months after an unprovoked seizure should be followed, and the accident risk associated with the planned activity due to possible seizure recurrence should be considered as well. Stays above 3500 m generally require individuals to be 6 months seizure free.

In patients with well-controlled epilepsy, infrequent seizures, and drug concentrations within the therapeutic range, trips to moderate altitudes are possible. Climbing, via ferrata tours, and tours in terrain with a risk of falling are problematic. In such cases, an individual risk assessment is necessary. Patients should have been seizure-free for at least 2 years. Focal seizures without loss of consciousness are associated with a lower risk. This also applies to stays at high altitude, provided that a cerebral space-occupying lesion as the cause of epilepsy has been excluded. Standard medication must be continued. Caution is required when other medications are taken concurrently, as carbamazepine and valproate are particularly prone to interactions. Emergency medication should be taken on the tour, and the mountain guide and tour companions must be informed about the condition.

21.4.3 Stroke, Transient Ischaemic Attack (TIA)

TIAs and ischaemic strokes have also been reported in high-altitude mountaineers without pre-existing diseases. They are presumably caused by a combination of polycythaemia, dehydration, a prothrombotic state, endothelial dysfunction, or impaired cerebral vascular autoregulation (Zhu et al. 2021; Liu et al. 2021). Following a stroke, there is a significant alteration in cerebral vasoregulation. Therefore, after a TIA or an ischaemic or haemorrhagic stroke, even if neurological deficits have fully resolved and cardiovascular risk factors are well controlled, it is recommended to avoid high-altitude stays for at least 3 months (Falla et al. 2021; Parati et al. 2018). In addition, any persistent neurological deficits that limit physical activity after a stroke, as well as common comorbidities such as diabetes mellitus, arterial hypertension, coronary heart disease, or heart failure, must be considered when considering approval for mountain sports. As with all significant pre-existing diseases, mountain tours should generally not be undertaken alone.

21.4.4 Other Neurological Disorders

Individuals with untreated high-risk malformations of cerebral vessels (e.g. aneurysm, arteriovenous malformation) or amyloid angiopathy should avoid high altitudes due to the increase in arterial blood pressure and the associated elevated risk of haemorrhage (Angelini et al. 2021; Falla et al. 2021).

Transient global amnesia can also occur at altitude; the prognosis is similarly favourable as for episodes at low altitude, and recurrences are rare. A single episode is not a contraindication to altitude stays (Falla et al. 2021).

Patients with restrictions in motion (e.g. Parkinson's disease, certain forms of multiple sclerosis, neuromuscular disorders) are generally aware of their disease-related limitations and often do not express a desire to visit high altitudes, even during stable phases of their illness, particularly if this involves physical exertion. Individual counselling is always indicated, depending on the severity of the condition and, for example, the extent of additional cold exposure. However, cable car journeys to moderate altitudes are usually tolerated well. Furthermore, dysfunction of the autonomic nervous system (e.g. in Parkinson's disease, multiple sclerosis) or of the respiratory muscles (e.g. in neuromuscular disorders) should be considered, as these may impair acclimatisation to altitude as well as peripheral neuropathies, which require specific protection measures in a cold environment (Angelini et al. 2021; Falla et al. 2021). In practice, these patient groups are much more likely to enquire about fitness to fly, which is generally not an issue.

21.5 Pre-existing Psychiatric Diseases

Mountaineering and mountain hiking can, in principle, improve mental health in individuals with psychiatric disorders (Ower et al. 2019) and can potentially be a part of therapeutic interventions even in severe mental illness (Sturm et al. 2012). The type of planned activity, altitude exposure, and remoteness of the tour should always be assessed according to the current individual mental health status. In untreated addiction disorders, particular caution is warranted due to cognitive impairment. There is an increased prevalence of eating disorders among some individuals who excessively engage in mountain sports (Habelt et al. 2023). In cases of severe anorexia (BMI <16 kg/m^2), strenuous physical activity should be avoided. In people taking sedative medication or drugs with extrapyramidal motor side effects, technically demanding tours must be avoided to prevent accidents.

Regarding altitude exposure it has generally been assumed that individuals with psychiatric pre-existing conditions rarely spend time at high altitude. However, recent surveys suggest that this is not the case (Hüfner et al. 2022). Individuals with pre-existing psychiatric conditions develop symptoms of AMS more frequently than those without (Hüfner et al. 2022). On the other hand, individuals who have experienced an episode of AMS have an increased risk of developing a psychiatric disorder in subsequent years (Wang et al. 2023). In principle, recommendations regarding altitude exposure for individuals with pre-existing psychiatric conditions are mainly based on expert opinion (Hüfner et al. 2019). Depressive and bipolar disorders may be exacerbated at altitude in the context of sleep disturbances. Many people experience mood changes at altitude, and the risk of such mood swings may be higher in those with pre-existing depressive or bipolar disorders. Therefore, stable pharmacological management is important. The use of sedative medication must be planned and discussed on an individual basis, and, if necessary, night-time departures must be considered as well. Psychotic symptoms may also be triggered at high altitude. It remains unclear whether the risk is increased in individuals with pre-existing psychotic disorders such as schizophrenia (Hüfner et al. 2023).

21.6 Pharmacological Prophylaxis and Treatment of Acute Mountain Sickness: Recommendations and Limitations in Specific Pre-existing Diseases

The use of standard medications for the treatment and prophylaxis of AMS may be limited or associated with significant risks in patients with pre-existing diseases. Important issues are briefly summarised (adapted from West [2013, p. 386]):

- Acetazolamide: Due to the resulting metabolic acidosis and the consequent need for hyperventilation, this medication should not be used in patients with reduced ventilatory capacity (FEV_1 <25%) or pre-existing hypocapnia. There is a relative contraindication in patients with impaired synthesis function of the liver and for those taking high doses of acetylsalicylic acid. Patients with renal diseases should also use acetazolamide with caution. It is contraindicated if the glomerular filtration rate (GFR) is below 10 ml per min/m^2 body surface area. If acetazolamide is taken prophylactically to avoid AMS, other diuretics should be reduced or discontinued. Topiramate and acetazolamide must not be combined (Luks and Hackett 2022).
- Dexamethasone: The main side effects of dexamethasone related to the nervous system are a sensation of being overexcited, sleep disturbances, and sometimes psychotic symptoms. In addition, it raises blood glucose concentrations, which must be considered when treating patients with diabetes, and it also increases the risk of gastrointestinal bleeding. In patients with type 2 diabetes, it should be considered that dexamethasone worsens insulin resistance (Hillebrandt et al. 2023).
- Nifedipine: Concomitant use of drugs metabolised via the CYP-450 pathway may result in reduced efficacy. The additive effect with other antihypertensive medications must also be considered.
- Phosphodiesterase inhibitors: Sildenafil and tadalafil should only be used at reduced doses in patients with renal failure. This also applies to patients with hepatic failure. Both drugs increase the risk of gastro-oesophageal reflux. They are contraindicated in combination with nitrates or alpha-receptor blockers due to the risk of severe hypotension.

Conclusion

In addition to the maximum planned altitude, it is necessary to clarify as part of medical counselling prior to a stay at high altitude, which additional factors the patient will be exposed to during the stay (e.g. climate zones, extent of planned physical exertion) and what impact these conditions may have on the course of the underlying disease or the risk of developing AMS. The availability of medical treatment on site is also crucial. Patients should only undertake high-altitude mountain activities during a stable phase of their illness, on optimal drug therapy and with a detailed emergency plan. This also includes informing companions and training them for handling emergency situations. For drugs used to treat AMS, such as acetazolamide, prednisolone, nifedipine, and phosphodiesterase inhibitors, side effects, interactions, and contraindications must be reviewed according to the pre-existing disease and ongoing drug therapy. Despite pre-existing conditions, patients may be fully fit for altitude, e.g. a well-controlled and well-instructed patient with hypertension or diabetes without end-organ damage. Patients who are asymptomatic after an uncomplicated myocardial infarction with an LVEF >45% and a normal age- and sex-adjusted exercise capacity on stress testing also have a low cardiac risk at Eastern European Alpine altitudes.

Contraindications to travel to high altitude include unstable underlying disease at low altitude, cyanotic heart defects, or necessity of long-term oxygen therapy. Altitudes >2500 m should be avoided in individuals with severe or markedly symptomatic pulmonary hypertension, advanced lung disease with FEV_1 <30% or total lung capacity <50%, within 6 weeks after AMI and within 3 months after a TIA or stroke, or in untreated high-risk cerebral vascular malformations (e.g. aneurysm, arteriovenous malformation).

Despite all limitations in individual patients, it should be emphasised that mountain sports have positive effects for most people, even those with pre-existing diseases.

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Orthopaedic Problems in Mountaineering

Thomas Hochholzer

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22.1 Knee Joint and Lower Extremity

The knee joint consists of three distinct compartments: the joint between the femur and tibia, the patellofemoral joint, and the tibiofibular joint. Degenerative changes and overuse can affect all three joints, with the patellofemoral compartment being particularly stressed during mountaineering.

22.1.1 Patellofemoral Pain Syndrome

There are numerous synonyms for the predominantly overuse-related knee pain: anterior knee pain, chondromalacia patellae, femoropatellar dysfunction or femoropatellar pain syndrome. All these terms describe pain in the region of the patella, which must be distinguished from the more common medial osteoarthritis of the knee, meniscal lesions or soft tissue overuse injuries such as patellar tendinopathy. These patellofemoral pain syndromes can occur more frequently during descent. They are usually classified as overuse reactions in the patellofemoral compartment and involve both passive and active structures.

Descending, and especially running downhill, places maximal stress on the knee joint and the femoral compartment, resulting in high patellar compressive forces and significant braking forces. “Modern mountain sports” such as trail running with downhill sections require an exceptional degree of muscular coordination. Nevertheless, the load on the knee joint and the retropatellar cartilage remains immense. According to some laboratory studies, patellar compressive force increases by up to 50% (Haid and Koller 2003). It should be noted that laboratory conditions probably underestimate the actual load experienced in the field, where the entire lower extremity, and especially the knee joint, must respond to uneven terrain, steps, scree, etc., with corresponding muscular stabilisation.

The pain is characterised by a dull, burning sensation beneath or behind the patella, which intensifies particularly during descent. Maximum flexion of the knee joint is also painful, and cold and wet conditions may be perceived as unpleasant. In more severe cases, swelling or intra-articular effusion of the knee may occur. Such symptoms often arise in spring or during the first mountain tours of the season, when the body is not yet accustomed to the load. Long mountain tours associated with significant fatigue are also common triggers. In addition to the primary overuse or excessive strain on the knee joint, further factors are often identified upon closer examination:

- Muscular imbalances.
- Congenital bony variations of the patella and the compartment.
- Degenerative changes.

Muscular deficits or imbalances occur in all muscle groups of the lower extremity and pelvis. These primarily functional disorders play a major role in causing symptoms. The quadriceps muscle, and in particular the vastus medialis, which is crucial for patellar stability, may be insufficient or simply poorly trained. This medial knee extensor is the most important dynamic stabiliser of the patella. Even in athletes, weakness of this muscle is sometimes observed, and it quickly undergoes visible atrophy in response to injury or disuse.

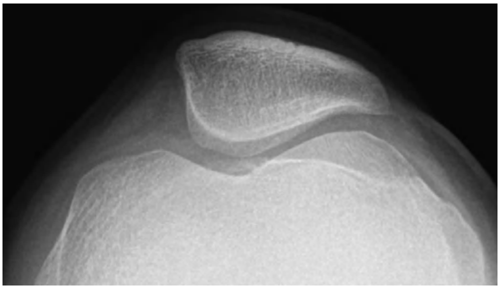
Shortened musculature in the thigh (iliotibial tract, quadriceps, hamstring muscles) and hip (iliopsoas, external hip rotators) regions can also affect the load on the patella. Specific sporting overloads, improper training, and lack of stretching lead to increased muscle tone or shortening of these muscle groups, which have a significant impact on knee mechanics and can increase the contact pressure of the patella against the femoral trochlea.

In addition, changes in pelvic position due to the strong pull of the quadriceps (one of the strongest muscles in the human body) or the iliopsoas can also influence the patella. Functional internal rotation causes malalignment of the femur with a tendency for lateralisation of the patella. This may be caused by muscle deficits, for example, of the external hip rotators. Malalignments of the foot, such as a flat-valgus foot, may also alter the rotational position of the tibia, affecting the patellofemoral joint. Overall, the knee joint, and especially the patellofemoral joint, should never be considered in isolation, but always in the context of the entire lower limb and pelvis.

In addition to the muscular situation of the patella, the bony configuration of the patella and the trochlea plays a decisive role in patellar tracking. Rotational malalignments of the distal femur, trochlear dysplasia, or congenital malformations of the patella, such as the so-called sail patella, result in uneven loading of the articular facets with high pressure peaks (▣ Fig. 22.1).

Furthermore, degenerative changes in bone and cartilage affect the load during downhill walking. In fact, in over 60–65% of individuals over the age of 55, degenerative changes on the retropatellar surface and the femoral trochlea can be detected radiographically.

The knee joint is therefore one of the joints most commonly affected by degenerative joint disease. However, it is extremely important to note that radiographic findings with more or less severe changes do not necessarily correlate with the patient's symptoms. As an examiner, one should always question whether the pathology found actually explains the patient's complaints. There are a number of very interesting cohort studies that clearly show that the radiological classification of osteoarthritis into four severity grades has little to do with the subjectively reported knee symptoms (Neogi et al. 2009).



▣ **Fig. 22.1** Moderately developed medial patellar facet in the tangential X-ray. This bony variant increases the pressure on the articular surface

22.1.2 Therapeutic Approach to Patellofemoral Pain Syndrome

What conclusions can be drawn from these facts by mountaineers or advising physicians in order to provide targeted advice to patients? The therapeutic approach will primarily be conservative. The less well-trained the mountaineer with knee complaints, the more emphasis must be placed on targeted preparation. The same applies to patients diagnosed with retropatellar osteoarthritis, which by no means necessarily precludes mountaineering. Many patients with congenital bony variants of the patella and trochlea will also benefit from a training programme and only rarely require surgical intervention.

Knee complaints during longer mountain tours can be a limiting factor. In acute cases or under "field conditions" (trekking, multi-day hikes, expeditions), the first question is whether the activity can be continued at all. In the presence of significant effusions and swelling of the knee joint, it will hardly be possible to continue due to pain. Non-steroidal anti-inflammatory drugs (NSAIDs) can help reduce pain. In cases of pain with effusion, cold compresses or NSAIDs dressings applied overnight can provide relief. If cold compresses are uncomfortable, warm or hot packs may be tried instead—the individual case will determine whether heat or cold is more pleasant.

In most cases, cold therapy is more effective in the initial stage of acute overload. Supportive knee braces or well-applied taping can reduce pain during walking and also help to centre the patella during this phase. Usually, the pain subsides on its own after a few days, once the movement pattern has adapted to the load. During this period, the weight of the rucksack should be reduced as much as possible, and stride length should be consciously kept short and walking speed slowed. Jumping or taking large steps should be avoided.

Subsequently, the focus shifts to developing muscular strength, flexibility (stretching), and coordination. A muscle strengthening programme or physiotherapy should not be limited to the knee joint. Depending on the diagnosis and muscle status, it should include a comprehensive training programme for the lower limb. This may involve training one to three times per week with cycling (or knee extension exercises on machines), a stretching programme for the quadriceps, hamstring muscles, and hip flexors and rotators, as well as coordination training on the MFT balance board or foam mats. The range of options has become very diverse.

Coordination training is extremely important and plays a crucial role in movement efficiency during mountaineering. In mountaineering, there are significant differences between experienced and novice climbers when walking in difficult terrain (moraines, tracks in deep snow, climbing with crampons, etc.).

For inexperienced mountaineers, these activities are not only unfamiliar but often very strenuous and associated with rapid fatigue. Experienced mountaineers, due to years of movement in challenging terrain, possess better coordination skills than beginners. Movement experience, surefootedness, freedom from vertigo, and efficient walking help conserve personal energy reserves and also protect against overloading the joints.

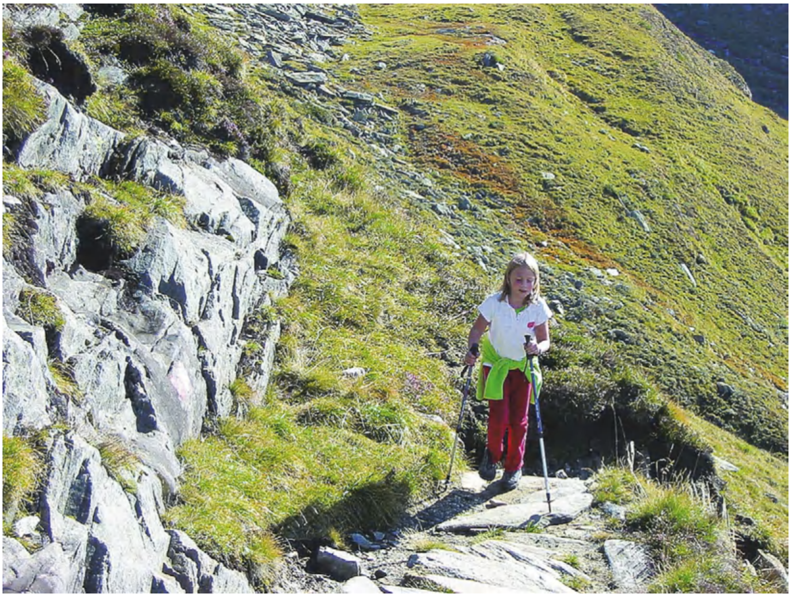
This important movement efficiency cannot be learned in just a few weeks or months; rather, it is the result of many years of walking and climbing in the mountains. It should also be assumed that these coordination skills gradually decline with age, but can be significantly improved through training. The term “performance reserve” is relevant here: Fatigue, exhaustion, illness, and also lack of training can markedly impair this movement efficiency and then lead to acute overload in the joint area.

22.1.3 Use of Walking Sticks

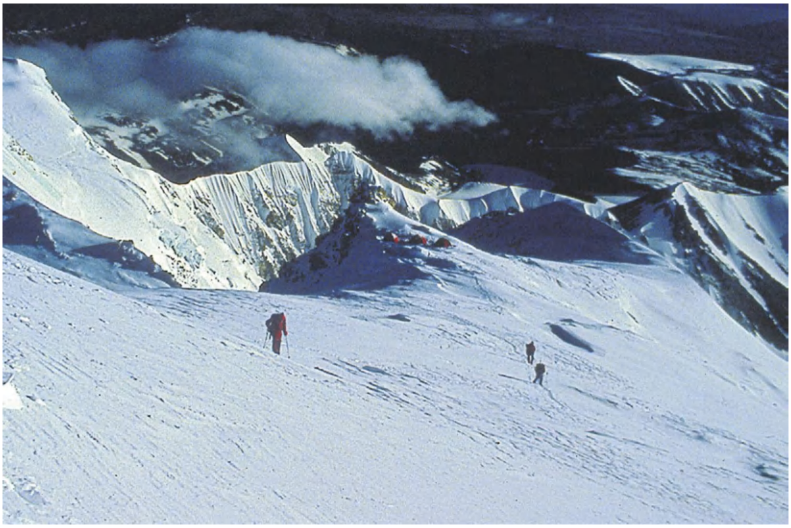
At this point, the use of walking sticks in mountaineering must also be discussed. According to a number of laboratory studies (Schwameder 2003; Neogi et al. 2009), it has been shown that the load on the knee joints during descent can be reduced by up to a third with the correct use of sticks. Nevertheless, the use of walking sticks in mountaineering should be considered in a differentiated manner: Children and adolescents do not require walking sticks when mountaineering, as they should first learn and improve their natural movement in the terrain and thus their coordination skills (Hochholzer 2003; ◘ Fig. 22.2).

For experienced and well-trained mountaineers, however, the use of sticks may tempt them to descend faster than they would without poles. This would greatly increase the load on the knee joints. The same effect occurs if, instead of increasing frequency, one increases stride length; here too, there are significant pressure peaks in the patellofemoral joint (Haid and Koller 2003).

The more degenerative changes are present in the knee joint, hip joint, or if there are complaints in the spine, the more the use



◘ **Fig. 22.2** Children and adolescents must acquire movement experience in alpine terrain without the use of walking sticks. (Image rights: T. Hochholzer)



◘ **Fig. 22.3** Close to the summit of Shisha Pangma above the last camp at 7300 m. Under these conditions, walking sticks can significantly facilitate the ascent and support the accessory respiratory muscles at this altitude. (Image rights: Thomas Hochholzer)

of sticks during descent can relieve these joints (◘ Fig. 22.3). Nevertheless, muscular "cushioning" when placing the feet on the heel must also be ensured.

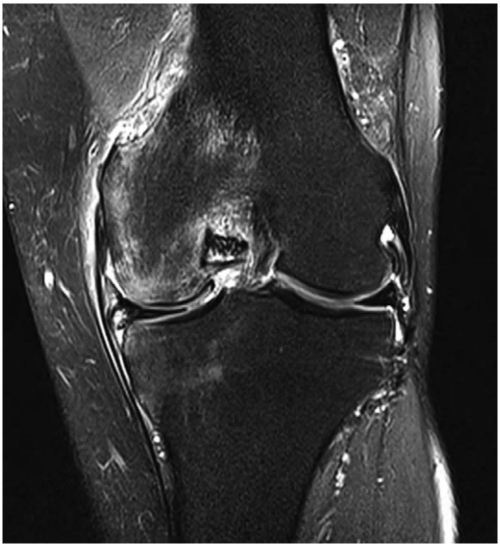
Preparation and equipment for a major undertaking in the mountains, especially in the presence of possible knee problems, should be tailored to individual needs.

Mountaineering boots should not be too heavy, but must still be stable and have a good sole. Women, who are usually accustomed to lighter footwear, should pay particular attention to the weight of the boots. Lightweight trekking shoes often have a more flexible and therefore more comfortable sole, but are often less stable than high-mountain boots and may have less slip resistance in wet conditions. The more degenerative changes present in the joints, the lighter the rucksack should be.

22.1.4 Bone Marrow Oedema of the Knee Joint

Mechanical or static overload can lead to bone reactions. With the introduction of MRI, such overload bone marrow oedemas are now easily diagnosable. Oedemas are frequently found in the tarsal bones and the knee joint (Biedert et al. 2007; Diehm et al. 2003; Walther and Stäbler 2006).

In mountaineers, the significant weight load of the backpack appears to be the cause of knee joint problems. For example, a 48-year-old, well-trained mountaineer developed pain in both knee joints after a two-week mountain expedition in Patagonia, carrying a backpack weighing up to 40 kg. In addition to the weight, the fatiguing nature of walking with reduced coordination in steep, rocky terrain involving shearing movements is likely also a contributing factor to this issue. MRI revealed extensive bone marrow oedema in both medial femoral condyles, with no other pathologies. Therapeutically, knee joints with bone marrow oedema often require unloading for up to 3 months (cessation of sports, possibly use of crutches). There are positive reports regarding the use of shockwave therapy. In recent years, these overload-induced bone marrow oedemas in mountaineers appear to be increasing, partly due to improved diagnostic techniques (▣ Fig. 22.4).



▣ **Fig. 22.4** Bone marrow oedema of the medial condyle of the knee joint in a 48-year-old mountaineer without trauma after an expedition carrying a heavy backpack of up to 40 kg

22.2 Back Complaints

Muscular tension in the shoulder and back muscles and stiffness of the vertebral joints are often the causes of back complaints during longer tours. Sleeping on hard surfaces in a tent or the unfamiliar burden of carrying heavy backpacks usually triggers these problems. Many back complaints are immediately associated with intervertebral disc herniation, but acute disc herniation during a tour is actually quite rare. Therefore, a precise analysis of the load situation on the back when carrying a heavy backpack is of great importance. Even when purchasing a backpack, one should be aware of its intended use, as manufacturers now offer a wide range of different models (e.g. touring backpack, daypack, lightweight backpack). In addition to optimal fit (there are now even backpacks designed specifically for women), it is important that a large proportion of the weight is borne by the integrated hip belt. When packing the backpack, heavy items should be stowed at the bottom and close to the body. This can significantly relieve pain in the shoulder and back area. With optimal weight distribution, posture can be optimised and the tension in the stabilising muscles reduced, thereby preventing premature fatigue. Trial hikes with the appropriate weight should definitely be undertaken before longer expeditions to test the suitability of the backpack. Several points should be considered regarding subsequent carrying comfort: Sometimes the shoulder straps of the backpack are adjusted too tightly, which can impair nerves and blood vessels in the armpit. Symptoms include tingling or numbness in the fingers and hands. In such cases, the backpack simply needs to be adjusted correctly and, if necessary, the weight reduced. Putting on and taking off the backpack with combined rotational and flexion movements places stress on the intervertebral discs, which are maximally compressed in the process. In individuals with pre-existing disc damage, this movement is the most common cause of problems. As a model, one can look to the local porters in Nepal, who often carry loads of more than 50 kg with the simplest carrying devices. At frequent rest stops, the load is supported on a raised stone platform; then the porter slightly bends at the knees, to remove the strain. This avoids rotational movements of the spine as well as deep bending. Overload of the vertebral and costovertebral joints, as well as the sacroiliac joint (SIJ), is much more common during mountaineering than disc herniation. Muscular overload and fatigue, as well as forced postures of the spine due to heavy backpack weight, can cause the so-called small vertebral joints or the sacroiliac joint to react with stiffness or, in the presence of degenerative changes (spondyloarthrosis, SIJ arthrosis), with inflammatory overload. The result is restricted movement, sometimes leading to forced postures. To protect the joint, muscle tone increases further. This increase in tone is mainly responsible for persistent lumbago symptoms. Such back problems can also be triggered by exposure to the cold. Therefore, wet and sweaty T-shirts should be changed quickly during walking breaks, or at least a jacket should be put on over them. Even a slight draught can lead to troublesome muscle tension. In acute cases in the mountains, treatment is generally limited to NSAIDs and reducing the weight in the backpack; further therapy may include injections and a muscular stabilisation programme.

22.3 Mountaineering with Hip and Knee Prostheses

In Germany, approximately 300,000 hip and knee joint endoprostheses are implanted each year, with numbers continuing to rise (Jerosch and Heisel 2009). The patients are becoming increasingly younger and are therefore often still very physically active. Whereas about 20 years ago, patients with endoprostheses were generally advised against participating in sports, or even prohibited, based on the belief that physical activity would promote prosthesis loosening, there has been a fundamental shift in recent years. In some cases, special skiing courses are now even organised for patients with endoprostheses. Sport with endoprostheses is generally possible, but certain basic prerequisites must be observed (see overview below).

Physical Activity with Endoprostheses

Prerequisites:

- At least 6 months post-surgery.
- Functional gait pattern.
- No pain.
- Good mobility and sufficient strength.
- No instability.
- No elevated inflammatory markers.

Contraindications:
- Infection.
- Poor mobility.
- Muscular insufficiency.
- Severe obesity.
- Revision endoprosthesis.
- Tendency to dislocation.
- Instability.

Naturally, there are sports that are optimally suited for patients with endoprosthetic implants. These include disciplines with low shear or rotational stress on the joint, without significant axial loading and without abrupt movements (Franke 2008; Schmidt-Sody et al. 2011; Wimmer et al. 2012). Sports such as swimming, cycling, and certainly also mountain hiking are recommended. Sports such as long jump, basketball, or tennis, which involve considerable peak pressures and shear forces on the prosthesis, should be avoided.

Important factors also include the patient's fitness, athleticism, and technical proficiency prior to surgery. An excellent skier will probably return to their sport more quickly and without major difficulties after surgery than someone who must first relearn the technique and movement patterns. Similarly, a patient who has refrained from sport for years before surgery due to pain and restricted mobility will find it more difficult to regain fine motor coordination than someone who only stopped their sport for a short period after surgery and subsequent rehabilitation.

Nevertheless, especially in skiing or ski touring, certain aspects—particularly environmental conditions—must be taken into account (see overview).

Skiing with Endoprostheses

Important prerequisites:
- Appropriate equipment (agile and stable skis, not too long).
- Sufficient endurance and strength.
- Low backpack weight.
- Good technique.
- Optimal environmental conditions (visibility, snow conditions, cold, etc.)
- Time limitation (do not continue until exhaustion).

As a consulting physician, one would not, for example, recommend that a patient go skiing if the slope is extremely icy and bumpy. The resulting impacts during descent place enormous stress on the artificial joint.

When it comes to climbing, each patient must be advised individually. In this context, even higher demands must be placed on the prosthetic implant in terms of stability (hip dislocation) and shear forces (knee).

Conclusion

In summary, it can be stated that: The older the mountaineers, the more degenerative joint diseases are present. The longer and more extreme the tours, the heavier the load to be carried, the more likely it is that an accompanying muscular training programme should be recommended for alpine activities, and that trekking poles should be used when descending. Beginners should first learn proper walking in the mountains without sticks, but also walking must be learned with sticks. Mountaineering with endoprostheses is generally possible, but requires individual consultation.

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Acute and Chronic Injuries in Sport Climbing

Volker Schöffl

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23.1 Terminology

The terminology of sport and free climbing encompasses a wide range of terms that require precise definition. Free climbing refers to the ascent of a climbing route using only natural features, with the rope and protection serving solely for the climber's safety. A route climbed in one continuous lead without falls is referred to as a "redpoint", and if the route is previously unknown to the climber, it is called an "on-sight".

Solo ascents with rope protection are termed "solo ascents", whilst unprotected solo climbs are known as "free solo". However, true "free solo" ascents are extremely rare, contrary to media portrayals. A route climbed with the rope anchored from above is referred to as "top-rope".

In addition to pure difficulty climbing, there is another essential sub-discipline of sport climbing: "bouldering". In English, a "boulder" is a large rock. Bouldering refers to rope-free climbing at jump height. In bouldering, "crash pads" or landing mats are used for protection.

23.2 Risk of Accidents

The risk of accidents in the various disciplines of alpine sports varies greatly depending on objective hazards, safety options, and individual risk tolerance. In pure sport climbing, however, objective hazards (e.g. rock or ice fall) are minimal. Various studies in recent years have shown that most injuries in sport climbing are due to overuse, and the risk of accidents is low.

An analysis of accident severity (UIAA MedCom Score; Schöffl et al. 2011) also demonstrates that most accidents are of minor severity (◘ Table 23.1). Nevertheless, the risk of a serious or even fatal accident always remains. For comparison with other disciplines and sports, sports medicine uses the relative accident risk per 1000 hours of participation. In sport climbing, this risk ranges from 0.2/1000 h in outdoor settings to 0.02/1000 h indoors (◘ Table 23.1; Schöffl et al. 2010, 2012).

Neuhof et al. (2011) describe a relatively even distribution between injuries to the upper (42.6%) and lower (41.3%) extremities. Overuse complaints more frequently affect the upper extremity, while acute injuries, such as those caused by falls, predominantly involve the lower extremity. Climbing frequency and difficulty level correlate with the incidence of overuse complaints (Schöffl et al. 2012). Most injuries occur to the lead climber, with falls being the most common cause of acute injuries, and performing difficult climbing moves the most frequent cause of overuse injuries (Schöffl et al. 2012).

◘ **Table 23.1** Accident risk in sport climbing

Study	Climbing discipline (geographical location)	Accident risk (per 1000 h)	Accident severity
Bowie and Allen (1988)	Rock climbing, bouldering, big wall climbing (Yosemite Valley, USA)	37.5[a]	Mostly minor accidents ISS score < 13 5% ISS 13–75
Schussmann et al. (1990)	Mountaineering and alpine climbing (grand Tetons, USA)	0.56 for accidents 0.13 for fatalities	23% of accidents fatal (NACA 7)[b]

(continued)

▫ **Table 23.1** (continued)

Study	Climbing discipline (geographical location)	Accident risk (per 1000 h)	Accident severity
Schöffl and Winkelmann (1999)	Indoor climbing (Germany)	0.079	3 NACA 2 1 NACA 3
Schöffl and Küpper (2006)	Competition climbing, Indoor World Championships 2005	3.1	16 NACA 1 1 NACA 2 1 NACA 3
Schöffl et al. (2009)	Icefall climbing (international)	4.07 for NACA 1–3	2.87/1000 h NACA 1 1.2/1000 h NACA 2 and 3 None >NACA 3
Backe et al. (2009)	Climbing (indoor and outdoor)	4.2 (of which 93% overuse injuries)	–
Neuhof et al. (2011)	Sport climbing accidents (Europe)	0.2	81.4% UIAA 2 18.2% UIAA 3 0.4% UIAA 4–6
Schöffl et al. (2013)	Indoor sport climbing (Germany) (515,337 climbing wall visits over 5 years)	0.02	15 UIAA 2 13 UIAA 3 2 UIAA 4
Schöffl, IFC MedCom (▶ 2013)	IFSC World Cup 2012	0.74	All UIAA 2

ISS injury severity score, *NACA* national advisory committee of aeronautics, *UIAA* Union Internationale des Associations d'Alpinisme

[a] Accident and fatality rate per 100 h calculated by Schöffl et al. (2010)

[b] NACA score retrospectively graded by Schöffl et al. (2010)

23.3 Injuries and Overuse Syndromes

Of 604 climbing injuries (1998–2001), 247 (41%) involved the hand and fingers (Schöffl et al. 2006). Fractures or polytrauma are much less common. In recent years, injuries to the hands and fingers have further increased. Of 911 climbing injuries recorded between 2009 and 2012, as many as 65.1% affected the hand and fingers. Shoulder injuries have also become increasingly common in our own patient population. ▫ Table 23.2 provides an overview of our own patient data from 1998–2001, 2009–2012, and 2017–2018.

Some of the injuries listed here, such as lumbrical shift syndrome or annular pulley ruptures, are specific to climbing and occur only rarely in the general population. This can make differential diagnosis challenging, especially when climbers represent only a small proportion of the patient population. The following section will therefore provide a more detailed discussion of certain climbing-specific injuries.

23.3.1 Annular Pulley Injuries

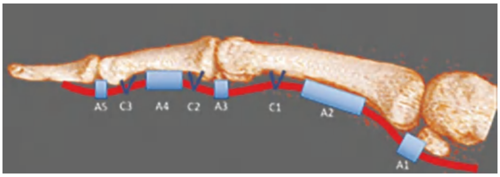
Injuries to the annular pulley system are the most common hand injuries among climb-

Table 23.2 The 10 most common injuries and overuse syndromes in sport climbers in 2017–2018, 2009–2012, and 1998–2001

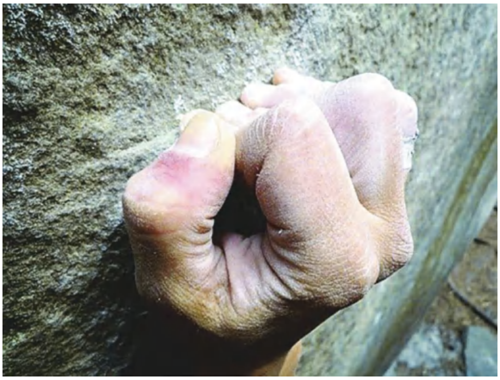
2017–2018 (*n* = 633)			**2009–2012 (*n* = 911)**			**1998–2001 (*n* = 604)**		
Injuries/overuse syndromes	**n**	**%**	**Injuries/overuse syndromes**	**n**	**%**	**Injuries/overuse syndromes**	**n**	**%**
Pulley injury (finger)	78	12.3	Pulley injury (finger)	140	15.4	Pulley injury (finger)	122	20.2
Tenosynovitis (finger)	67	10.6	Capsulitis (finger)	87	9.5	Epicondylitis	51	8.4
Capsulitis (finger)	49	7.7	Tenosynovitis (finger)	80	8.8	Tenosynovitis (finger)	42	7.0
Knee injury	45	7.1	SLAP lesion	51	5.6	Capsular strain (finger)	37	6.1
SLAP lesion	37	5.8	Epicondylitis	50	5.5	Abrasion	34	5.6
Impingement (shoulder)	34	5.4	Impingement (shoulder)	40	4.4	Back pain	24	4.0
Wrist overuse	22	3.5	Flexor tendon strain (finger)	36	4.0	Knee injury	14	2.3
Epicondylitis	21	3.3	Dupuytren's contracture	30	3.3	Fractures	14	2.3
Epiphyseal plate injury (finger)	19	3.0	Capsular strain (finger)	25	2.7	Capsulitis (finger)	13	2.2
Spinal injury	18	2.8	Flexor tendon ganglion (finger)	19	2.1	Flexor tendon ganglion (finger)	11	1.8

SLAP superior labrum anterior to posterior ers and only recently have annular pulley injuries also been described in the general population (◘ Fig. 23.1). The annular pulley system of the fingers consists of five annular pulleys (A1–5) and three cruciate pulleys (C1–3). There is a very high force exerted on the A2, A3, and A4 pulleys when using the so-called crimp grip position (◘ Fig. 23.2), which is frequently used when holding small holds, which potentially leads to strain or rupture (Schöffl et al. 2006). Symptoms include local tenderness with swelling of the proximal phalanx, sometimes a mild haematoma, and when the flexor tendon is tensed against resistance, visible bowstringing of the tendon. Following a clinical suspicion and exclusion of bony injury, ultrasonography (showing increased distance between the flexor tendons and the bone) can differentiate between pulley strain, single pulley rupture, or multiple ruptures.

In cases of single pulley injury (Grade I–III according to Schöffl et al. 2003a), conservative management is indicated, with immobilisation and early functional rehabilitation. In cases of multiple injuries (Grade IV), surgical reconstruction should be considered (◘ Fig. 23.2). The outcomes of conservative treatment are very good; the initial loss of finger strength resolves, and athletes typically regain their previous level of performance. Taping of the injured finger using biomechanically designed H-tape (◘ Fig. 23.3) should be applied therapeutically at first and later as support during sports activities (Schöffl et al. 2003a).



◘ **Fig. 23.1** Annular pulley system, schematic representation



◘ **Fig. 23.2** Crimp grip position in climbing

A strip of tape approximately 1.5 cm wide and 8–10 cm long (depending on finger thickness) is torn at both ends, leaving a central bridge about 1 cm wide and two tabs of 0.75 cm on each side. Two of these tabs are passed under the joint and firmly fixed. The joint is then flexed, and the remaining two tabs are passed over the joint and also firmly fixed. In this way, the injured pulley can be unloaded, and in cases of tenosynovitis, the deflection angle of the flexor tendon at the end of the pulley can be reduced, thereby decreasing friction. ◘ Table 23.3 presents the treatment guidelines for pulley ruptures of different grades.

23.3.2 Tenosynovitis

Tenosynovitis (inflammation of the tendon sheath) is the most important differential diagnosis to pulley injury and the most common overuse syndrome in climbers. It may develop insidiously due to cumulative overload, but it can also present acutely following particularly intense training or a strenuous day of climbing.

Clinical examination reveals tenderness on the palmar side, usually at the level of the A2 pulley or in the region of the carpus, often radiating into the forearm. Diagnosis is confirmed by ultrasound, which demonstrates a characteristic ring of fluid (halo sign) in cross-section.

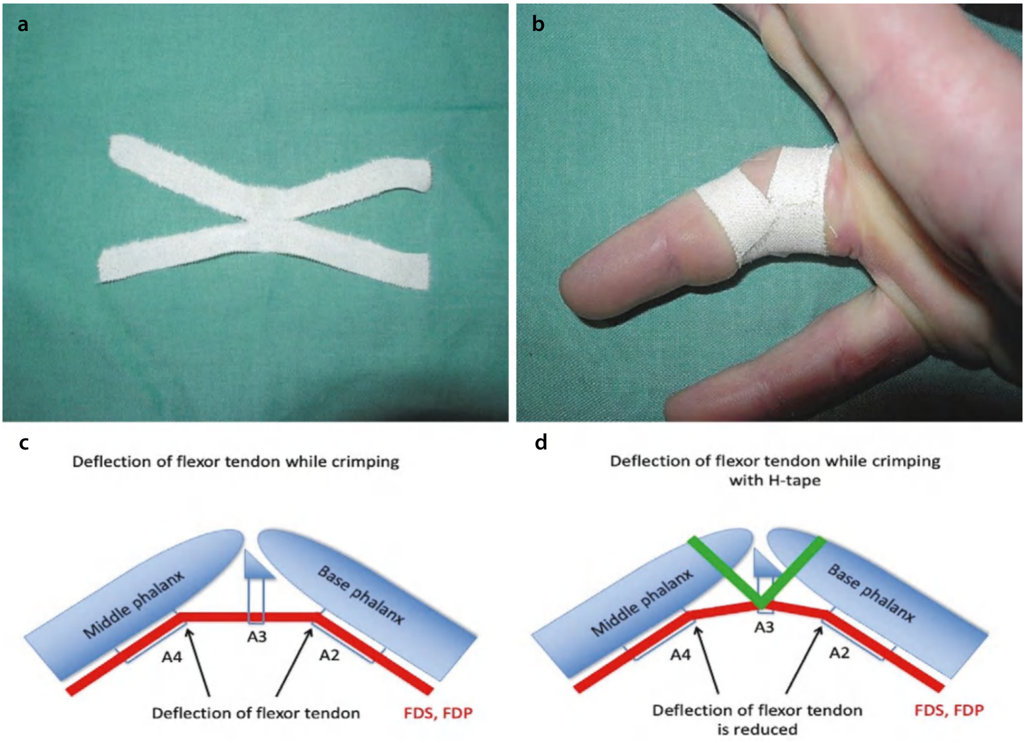

a
b
c
Deflection of flexor tendon while crimping
Middle phalanx
Base phalanx
A4
A3
A2
Deflection of flexor tendon
FDS, FDP
d
Deflection of flexor tendon while crimping with H-tape
Middle phalanx
Base phalanx
A4
A3
A2
Deflection of flexor tendon is reduced
FDS, FDP

Fig. 23.3 **a–d** H-tape for the treatment of pulley injuries: clinical application and biomechanical effect. *FDS* flexor digitorum superficialis; *FDP* flexor digitorum profundus

As increased fluid accumulation in the digital tendon sheaths is frequently observed in climbers even in the absence of symptoms so the examination should always be compared with the contralateral healthy finger. Initial treatment may include immobilisation with a splint along with rest from sport, medicating with non-steroidal anti-inflammatory drugs (NSAIDs) and enzyme preparations, ice massage, brushing massage, and, if necessary, sulphur baths.

In chronic cases, local corticosteroid injection—strictly into the tendon sheath and not the tendon itself—may be required. Open tenosynovectomy is indicated only in exceptional cases. In mild cases, reduction of load and taping during sporting activity (H-taping) are often sufficient. In rare cases, arthritic changes (dorsal osteophytes) may also directly irritate the extensor tendons.

23.3.3 Fractures and Epiphyseal Fractures in Adolescent Climbers

Twisting in finger pockets and cracks can result in simple base fractures of the distal phalanx as well as severe burst and spiral fractures. More severe fractures, especially when associated with extensive soft tissue defects following rockfall injuries, often require surgical intervention.

Of particular concern are the increasingly frequent atraumatic epiphyseal fractures (stress fractures) in adolescent climbers reported in recent years (Fig. 23.4).

These are usually Aitken type I and II fractures (Salter-Harris II–III) (Schöffl et al. 2003b). Recently a new specific classification has been developed by Schöffl et al. (2025) A

Table 23.3 Treatment guidelines for annular pulley rupture (Schöffl et al. 2007)

	Grade I	Grade II	Grade III	Grade IV
Injury	Pulley strain	Complete rupture of A4 or partial rupture of A2 or A3 pulley	Complete rupture of A2 or A3 pulley	Multiple ruptures, e.g. A2/A3, A2/A3/A4, or single rupture (A2 or A3) in combination with injury to the lumbrical muscles or collateral ligaments
Therapy	Conservative	Conservative	Conservative	Surgical
Immobilisation	No	10 days	10–14 days	Postoperative 14 days
Functional therapy	2–4 weeks	2–4 weeks	4 weeks	4 weeks
Pulley protection	Tape	Tape	Thermoplastic ring, soft cast ring	Thermoplastic ring, soft cast ring
Light sport-specific activity	After 4 weeks	After 4 weeks	After 6–8 weeks	After 4 months
Full sport-specific activity	After 6 weeks	After 6–8 weeks	After 3 months	After 6 months
Tape protection during sport-specific activity	3 months	3 months	6 months	> 12 months

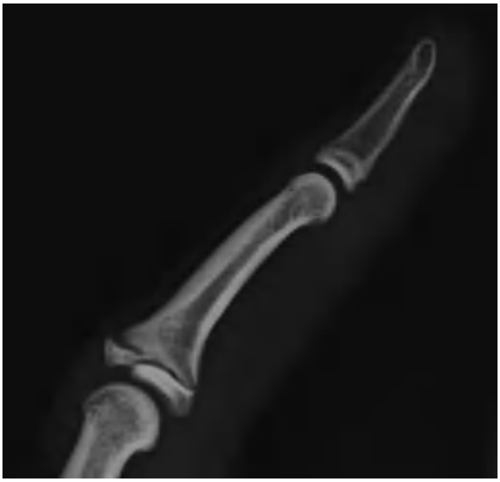


Fig. 23.4 Epiphyseal fracture of the proximal interphalangeal joint

definite traumatic event is rarely reported. All adolescents described gradually increasing pain and swelling in the proximal interphalangeal joint. These injuries must be taken very seriously, as inadequate treatment can lead to irreversible damage.

Recurrent finger pain and swelling in adolescent climbers must always be investigated radiologically, and if clinical suspicion persists despite a normal conventional X-ray, MRI should be performed. Acute injuries with displacement of the epiphyseal fragment should be treated with mini-osteosynthesis, while chronic malunions may require epiphysiodesis with Kirschner wires Schöffl et al. (2025).

In cases with no or minimal displacement, brief immobilisation and a 6- to 8-week break from sport are sufficient. It is also important to provide sports medicine education, monitor adolescent competitive climbers, and avoid specific high-load training methods (campus board).

23.3.4 Lumbricalis Shift Syndrome

The lumbricalis shift syndrome is a rare but climbing-specific clinical entity. When pulling on a "one-finger pocket" or during specific single-finger training, the pulling finger is extended while the other fingers are flexed. In this position, the loaded profundus tendon is displaced so forcefully against the unloaded neighbouring profundus tendons that the common origins of the lumbrical muscles are shifted against each other, potentially resulting in partial muscle ruptures and strains. Clinical validation is straightforward. If the climber pulls with the injured finger, while the adjacent fingers are flexed, they report pulling pain on the side of the proximal phalanx. If the adjacent fingers are extended during the provocation test, no pain is present. Treatment consists of local measures, taping, and gentle stretching of the lumbrical muscles.

23.3.5 Injuries from Falls

Thanks to modern belay devices and improved equipment, safe falling has become possible for sport climbers and is, in fact, an essential component for achieving the highest grades of difficulty. Up to 10 falls per day are quite normal. Schubert (DAV Safety Circle) distinguishes between deliberate, intentional jumping, which is common in sport climbing, and uncontrolled falls, which are associated with a higher risk of injury.

In sport climbing, as opposed to alpine climbing, the sit harness is standard, and injuries to internal organs are therefore very rare. Suspension syndrome (orthostatic collapse) occurs only in unconscious climbers. In general, suspension syndrome refers to bodily harm caused by circulatory collapse while hanging freely in a harness.

The most common injuries from falls are trauma to the lower extremities, caused by two fundamentally different mechanisms: impact trauma and fall-from-height trauma. Impact trauma occurs when the rope pulls the falling climber against the rock face.

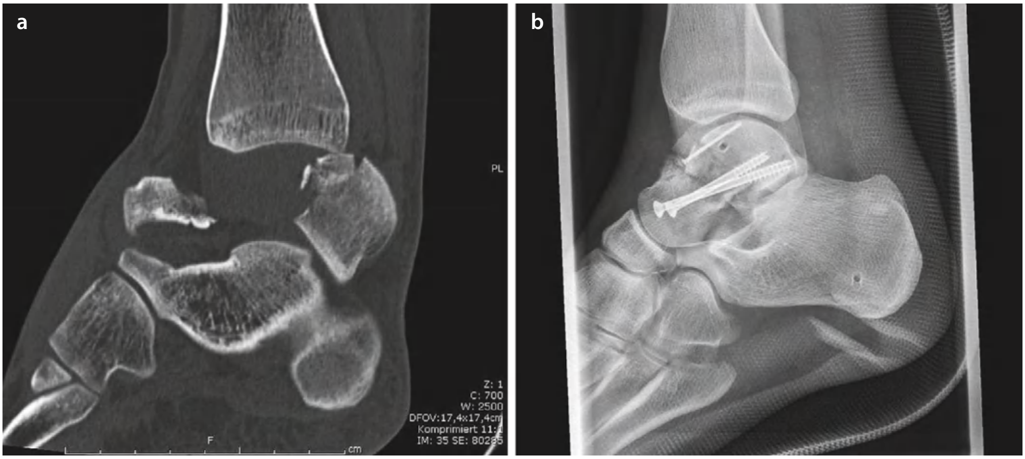


Fig. 23.5 Fracture dislocation of the talar neck due to impact trauma after a 4-metre lead fall. **a** Accident CT scan. **b** Postoperative image

This is mainly caused by short falls with a high fall factor on less steep terrain. This typically results in contusions and fractures of the forefoot and midfoot, as well as the talus and calcaneus (Fig. 23.5). Fall-from-height trauma occurs when the climber falls unimpeded to the ground. This mainly happens during bouldering, or in climbing when falling before clipping the rope into the first bolt, or due to belaying errors. This mechanism primarily leads to inversion injuries, which may result in minor sprains or, in more severe cases, lateral ligament ruptures and fractures.

During a fall, the arms should be extended sideways to achieve a stable position (Fig. 23.6). At the end of the fall, when the rope pulls the body towards the wall, the feet should be brought forward to cushion the impact. Similarly, the hands should protect what is most important, i.e. they should be brought forward and, if necessary, placed in front of the head or chest. Once the fall is completed, the hands should be placed on the rope tie-in point to prevent tipping backwards. Under no circumstances should there be an attempt to grab the rope during the fall itself as severe injuries from

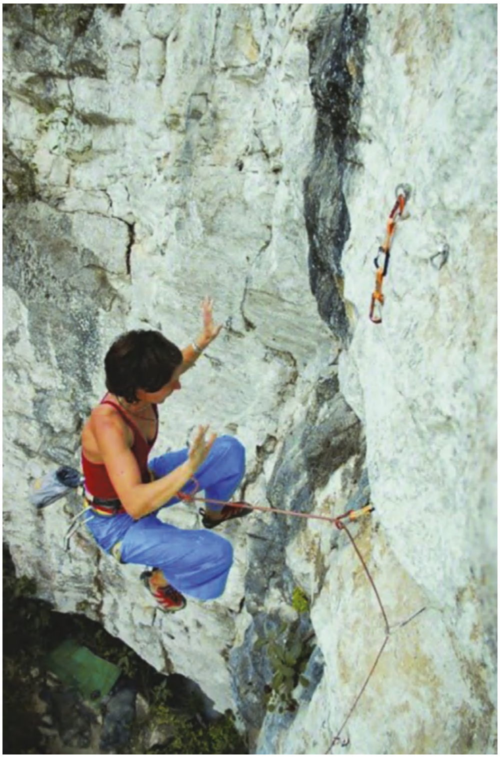


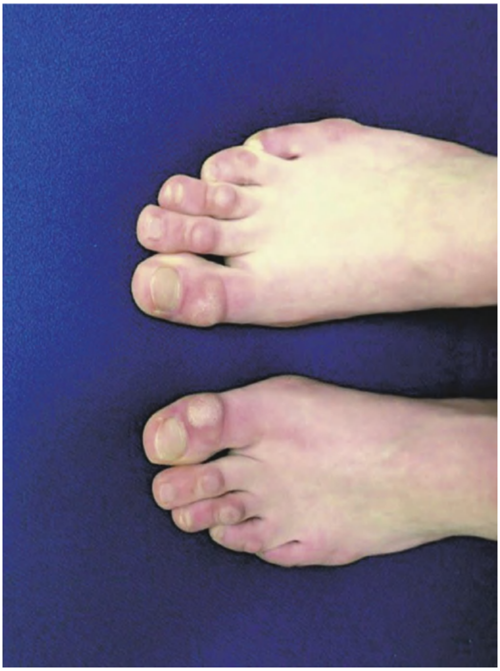
Fig. 23.6 Isabelle Schöffl demonstrates the recommended arm position during a fall on the route "Calcaneus", 7c, Laos. (Image rights: V. Schöffl, courtesy of I. Schöffl)

rope entanglement, including finger or hand amputation, may result (Hochholzer and Schöffl 2005).

23.3.6 Foot Problems

Foot problems caused by tight climbing shoes are common, as an optimal transfer of force onto the often very small footholds requires a very snug fit. In such shoes, the toe joints are not extended but held in a flexed position. This leads to chronic forefoot problems such as calluses, pressure points, or even hallux valgus (◘ Fig. 23.7).

Such tight shoes are only necessary at the performance level. In the recreational sector slightly more comfortable sizes can be used without difficulty, which means that most significant foot problems occur less frequently. An increasing number of shoe manufacturers are responding to this by offering orthopaedically adapted climbing shoes with inner linings, as shown in ◘ Fig. 23.8.

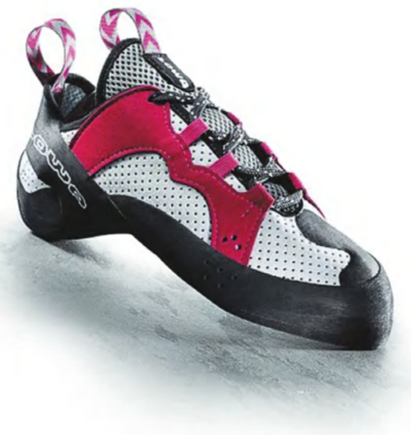


◘ **Fig. 23.7** Chronic calluses caused by very tight climbing shoes

Overall, it should be noted that many of the differential diagnoses discussed here relate to elite sport and rarely occur in recreational climbing. Climbing has now become established as a safe recreational and popular sport. It exercises the whole body and can be fun to practice. This fun full-body training is increasingly being incorporated into school and children's sports and has a firm place in physiotherapy and medical rehabilitation.

23.3.7 Measures to Prevent Accidents

Active athletes can assist accident prevention. There are various options for doing this. For example, when bouldering, a crash pad should always be used. This is a specially designed two- or three-layer hard foam mat in the form of a large rucksack and when unfolded it provides a total area of approximately 1.5–2 m^2, which is used as a landing mat.



◘ **Fig. 23.8** Modern climbing shoe made from non-stretch material with padded and antimicrobial inner lining. (Image source: Lowa, Jetzendorf, Germany, with kind permission)

Mats must also be available in the vicinity of indoor climbing walls. For steeply overhanging bouldering walls, soft mats with a thickness of at least 30 cm are recommended. Here, due to the angle of the wall, climbers often fall uncontrollably onto their backs. However, the gaps between individual mats can pose a problem. Many accidents occur when a foot gets caught in a mat gap, resulting in a subsequent twisting injury. Good manufacturers offer mat-bridging elements to counteract this.

In the lead climbing area of indoor facilities, mats need to be lower and firmer. Here, injuries are mainly caused by falls from a low height, and soft mats would only increase the risk of twisting injuries. Regarding route protection, only the first ascenders need to be advised. The first bolt should be placed at a reasonable height, and the subsequent bolts positioned so that the climber does not fall to the ground when clipping or in the event of a fall. When belaying, care should be taken to avoid catching a fall too abruptly or too short, i.e. the so-called fall factor should be minimised as much as possible.

Even with static belay devices, such as the GriGri or Cinch, dynamic belaying can be achieved by the belayer jumping slightly. Mistakes in this area occur mainly among beginners; correct belaying must be practiced. The aim of all activities should be to avoid serious accidents while still allowing the climber the greatest possible experience.

Measures to Prevent Accidents

- Crash pad for bouldering.
- Mat protection in indoor areas.
- Mat-bridging elements.
- Route protection.
- Belaying technique.

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Risk Management and Accident Prevention in Mountain Sports: Findings from Alpine Field Research

Martin Schwiersch

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24.1 Background, Research Objective, Study Design, and Summary of Findings

24.1.1 Background and Research Objective

"It is safe when nothing happens but when a lot happens it is dangerous". This is an initial intuitive guideline for human decision-making. We assess the acceptability of alpine activities based on assumptions about accident frequencies. These assumptions guide our conclusions in the event of real alpine accidents. "Again?" we think when confronted with an avalanche incident. What we cannot know is how many ski tourers refrained from dangerous tours that day, and how many groups chose routes with lower avalanche risk. Conversely, the fact that no accident has occurred so far does not in itself justify the risk taken. It is quite possible that thousands of indoor climbers in Central Europe are putting themselves at risk every day by belaying with a "slack rope"—it is just very uncommon for lead climbers to fall unexpectedly near the ground.

For these two reasons, accident rates alone are poor guides. Firstly, the "base rate" (Schwiersch 2004) is unknown. How many ski tourers were active in the Alps; how many decided against a tour; and how many climbers belay with a "slack rope"? Secondly, the absence of an accident can mask actual risk behaviour. It is therefore time to replace "opinions" about risks with knowledge of risks taken and behavioural errors.

24.1.2 Methodological Approach

The safety research division of the German Alpine Club (DAV) therefore decided to investigate how indoor climbers, ski-touring groups, and mountain hikers actually behave during their respective activities. Methodologically, this led to field studies with the following approach.

24.1.2.1 Attempt to Obtain "Typical" Field Samples

For *indoor climbing*, large public climbing gyms were visited at all opening times on typical days of attendance. Further, care was taken to ensure that the climbers observed were selected at random during their time in the gym and also with regard to the route climbed. For *ski touring*, typical ski-touring mountains in various regions were selected at different avalanche risk levels, and the ski-touring groups present on the chosen observation day were studied. For *mountain hiking*, a similar approach was taken, with different trail difficulties and tour lengths considered.

24.1.2.2 Random Selection of Study Participants

"Whoever is present is eligible". For indoor climbing and mountain hiking, potential participants were approached in advance, whereas for ski touring it was before and after their tour. There were very few refusals. Due to the high number of participants at indoor climbing gyms, a random selection of those entering the gym was made.

24.1.2.3 Focus of Observation on Safety-Relevant Behaviour

In all three areas, the behaviours of interest were defined in advance and categorised and compiled into an observation system. For *indoor climbing*, potential behavioural errors were listed for each activity—lead climbing, top-rope climbing, lead belaying, and top-rope belaying—which observers on site were required to mark as "occurred" or "did not occur". In *ski touring*, both the terrains traversed by the observed group were categorised according to risk factors, and the safety-relevant behaviour displayed was recorded. In *mountain hiking*, the focus was on the level of exertion, surefootedness, and the time required. Exertion and surefootedness were rated by the observers using a scale and subsequently assessed for appropriateness through consensus.

Preliminary studies showed that the respective observation categories were appropriate and comprehensive for the research question. It was also demonstrated that the observers independently arrived at similar assessments (Schwiersch et al. 2007).

After the observation phase, all participants were surveyed using questionnaires (indoor climbing and mountain hiking) and, in the case of ski touring, additionally through structured individual interviews (study 2005) or, in the later study (2020–2022), with one interviewee per group before and after the tour.

24.1.3 Studies and Samples

Between 2003 and 2005, 278 participants in climbing gyms, 122 in ski touring, and 208 in mountain hiking were studied, including men and women aged 16 and over. Due to significant advancements in belay devices for climbing, a further observational study was conducted in 2012 in 11 climbing gyms with 368 participants. From 2020 to 2022, a second field study in the area of ski touring/freeriding was conducted, involving 112 ski-touring groups with a total of 345 individuals.

Further details on sociodemographics and results can be found in Mersch et al. (2005, 2007), Schwiersch et al. (2005, 2006), Funk et al. (2012, 2013), and Brugger et al. (2022a, b, 2023).

24.1.4 … and the Result in Summary (Take Home Message I)

People who voluntarily go mountain hiking, ski touring, or climb indoors are not reckless risk-takers. We did not generally observe overstrained casual hikers in hazardous terrain, skiers intoxicated by deep powder who whoop as they descend avalanche-prone slopes, or climbers distractedly flirting with the woman next to them while forgetting about their lead-climbing partner.

The individuals observed generally knew what they were doing—they had consciously chosen their activity after weighing up the risks. They were aware of potential behavioural errors (indoor climbing), the current avalanche risk level (ski touring), and the demands of the hike (mountain hiking). They generally assessed their own abilities well—and in terms of observed behaviour, appropriate safety practices clearly outweighed errors in both indoor climbing and mountain hiking.

Any distorted perceptions can be justifiably refuted. We must also let go of other prejudices:

- Women do not display better or worse behaviour than men.
- Younger people do not expose themselves to more risk than older individuals.
- Greater experience alone does not necessarily lead to better behaviour.

This applies to both indoor climbers and mountain hikers. (These questions could not be investigated in the ski-touring study, as only groups were studied in this context.)

However, there is still a need for change. In all areas, there are many behavioural errors that could be avoided. The potential solution is also empirically supported: Training and a focused engagement with the respective activity are beneficial.

24.2 Risk Management in Ski Touring

24.2.1 Avalanche-Related Knowledge

All ski-touring groups (◘ Fig. 24.1) were interviewed in a structured manner before and after their tour regarding their ava-

Fig. 24.1 Ski touring

lanche knowledge and the tour they had undertaken. The results of the 2020–2022 study are reported here. During the interviews, most ski-touring groups proactively stated the avalanche danger level that applied on the day of observation and for the tour they completed. These statements were generally correct. Also, compared to the 2005 study, there was an increase in awareness of the avalanche danger level (Fig. 24.2).

This is not a trivial matter, as the avalanche danger level can change daily and may vary regionally and, in some cases, by altitude. This information therefore needs to be specifically found and noted.

For on-site avalanche-related decision-making, the "avalanche problems" represent an important additional piece of information in the avalanche bulletin. These are known to a significant proportion (just under two-thirds) of the groups (Fig. 24.3).

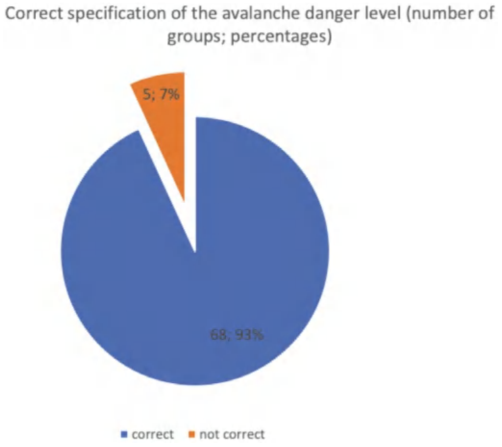
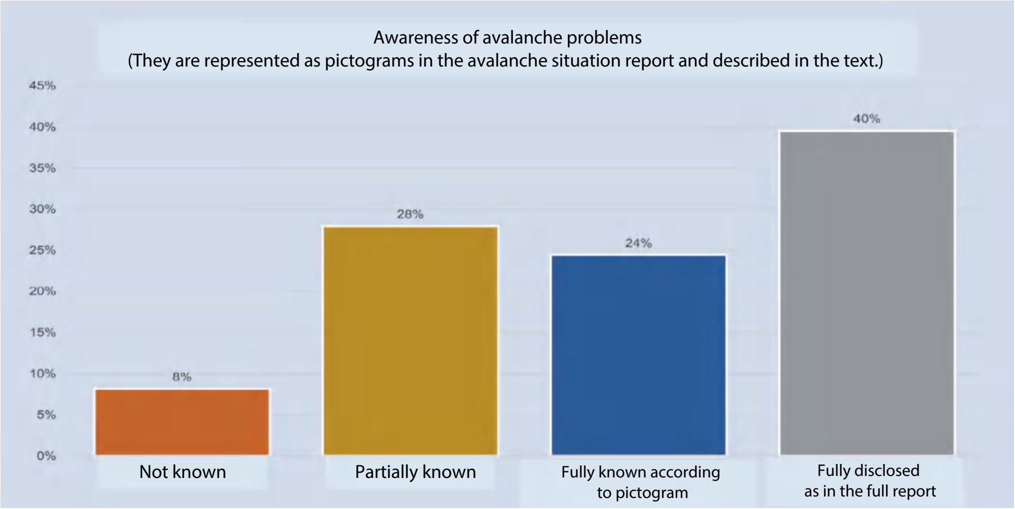


Fig. 24.2 Ski touring: correct specification of the avalanche danger level (the number of groups; percentage values). (Image rights: German Alpine Club - DAV, with kind permission)

The 2005 study showed that the additional information in the avalanche bulletin is more likely to be recalled by those participants who

- have formal training,
- rate their knowledge of snow and avalanche science as good,
- use strategic avalanche decision-making tools (e.g. reduction method, "stop or go", Snowcard) as decision aids,
- are able to accurately assess slope steepness.



▪ **Fig. 24.3** Ski touring: knowledge of avalanche problems (these are depicted as pictograms and described in the text of the avalanche bulletin). (Image rights: German Alpine Club—DAV, with kind permission)

> Those who engage intensively with the subject of avalanches benefit most from the information provided in the avalanche bulletin.

24.2.2 Avalanche-Related Assessments and Behavioural Decisions of Ski-Touring Groups

Similar results were observed in both studies; the findings from the 2020–2022 study are reported here. On the survey days, the avalanche danger level was predominantly "moderate" or "considerable", so the observed groups were required to adapt their tour decisions and route choices to the avalanche risk.

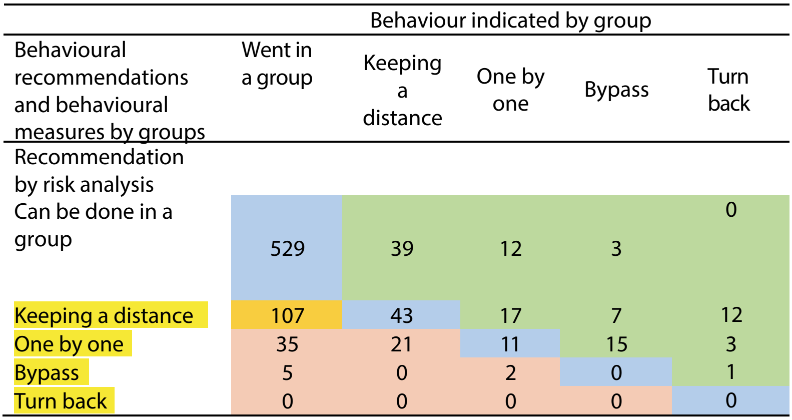
In general, the groups selected tours appropriate to the conditions: 21 groups (19%) chose tours without avalanche-prone locations; 64% chose tours with one to a maximum of three hazardous locations. For 66% of the hazardous locations, the recommended behaviour was to "maintain spacing for load reduction", meaning these locations could be traversed with appropriate precautions.

However, hazardous locations are not always fully identified: 62% of the hazardous locations on the intended tour were identified as such before the tour began, and 56% of the hazardous locations were identified on the actual tour (the difference is not significant).

▪ Figure 24.4 shows the adequacy of the groups' risk management at terrain and hazard locations.

Due to the generally defensive and proportionate tour decisions, appropriate behaviour predominated at 68% (583 measures at 862 locations), when combining avalanche-safe terrain sections ("terrain sites") and avalanche-exposed sections ("hazard sites") identified on the survey day.

If only the hazard points are considered, just 19% (54 out of 279 hazard points) are traversed in accordance with the risk analysis recommendations of the study. Most "risky" behaviour involved group travel at 107 locations where the risk analysis recommended maintaining a spacing for load reduction; that is, simply by observing appropriate spacing, correct behaviour at hazard points could be increased to 58% overall. Major discrepancies between rec-



	Behaviour indicated by group				
Behavioural recommendations and behavioural measures by groups	Went in a group	Keeping a distance	One by one	Bypass	Turn back
Recommendation by risk analysis					
Can be done in a group	529	39	12	3	0
Keeping a distance	107	43	17	7	12
One by one	35	21	11	15	3
Bypass	5	0	2	0	1
Turn back	0	0	0	0	0

Fig. 24.4 Ski touring: risk management at terrain and hazard locations. (Image rights: German Alpine Club—DAV, with kind permission). The ski-touring groups passed 862 terrain locations (= locations that could potentially become avalanche-prone), of which 279 were classified as hazardous by the study on the survey day *(highlighted in yellow)*. Depending on the level of danger at each location, different behavioural recommendations were made. *Blue:* Agreement between the recommended behaviour and the behaviour observed at terrain locations. *Green:* overly cautious behaviour at terrain locations. *Red:* risky behaviour at terrain locations relative to the recommended behaviour

ommendations and actual behaviour are rare: At five locations, three groups travelled together despite a detour being recommended.

These discrepancies could be reduced if ski tourers used clear, practical risk management systems (“strategic avalanche awareness”). Such systems do exist, but as both studies show, they are rarely applied in practice.

> Despite generally good risk management, avalanche-related hazard points are not sufficiently well identified. “Strategic avalanche awareness” could improve this, but in practice it is seldom used.

24.3 Risk Management in Mountain Hiking: Surefootedness and Fitness of Mountain Hikers

To safely complete a mountain hike (Fig. 24.5), aside from sufficiently stable weather conditions, surefootedness and physical fitness are required. In this context, “risk management” means choosing a route that matches fitness level and where surefootedness, for example in rugged terrain, is adequate.

Fig. 24.5 Mountain hiking

Both factors were assessed after observer training by monitoring the participants during the hike and rated on a five-point scale (1 = very good, 5 = poor). The participants’ walking times were also recorded. To determine whether fitness could be classified as “adequate”, the following approach was used: The DIN standard (German national

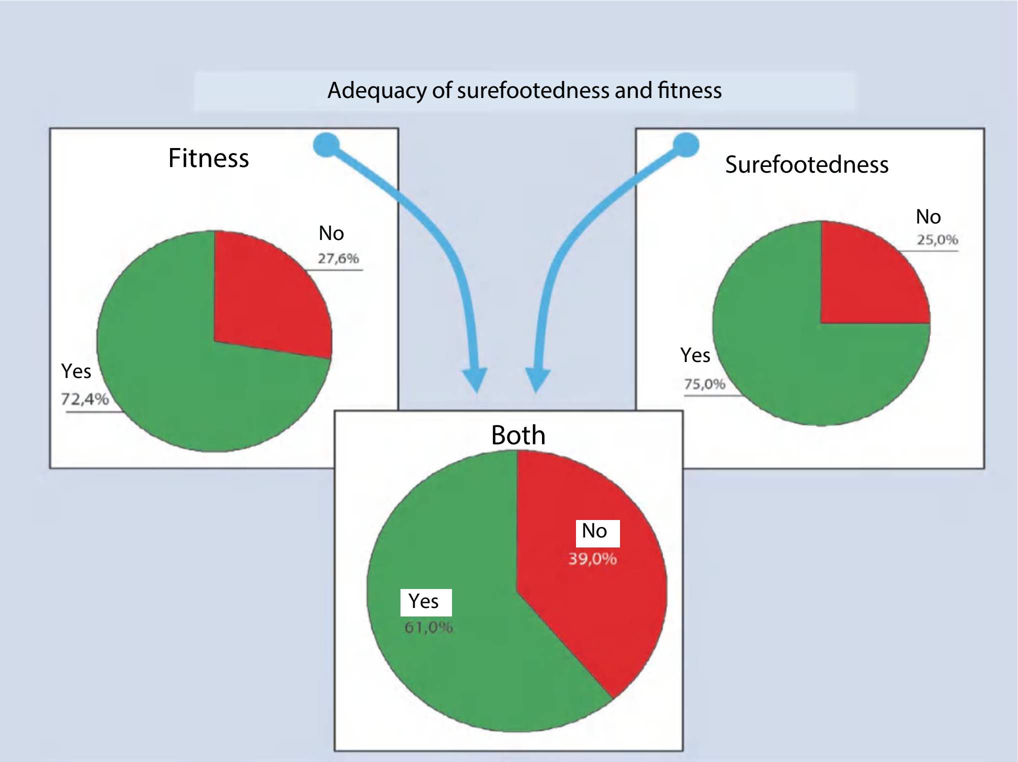


Fig. 24.6 Mountain hiking: adequacy of surefootedness and fitness. (Image rights: German Alpine Club—DAV, with kind permission)

standard) for calculating walking times was used as a "benchmark" for appropriate timing. The observed physical exertion was then related to the time taken, since those who walk faster are allowed to be more fatigued. To assess the adequacy of surefootedness, the difficulty of the mountain path was compared to the observed surefootedness. Figure 24.6 shows the results.

The observed individuals were, for the most part, physically fit for the chosen route and completed it with sufficient surefootedness. Both surefooted and adequately fit for their route were 61% of the observed individuals.

The mountain hikers were also surveyed after the hike. Those who hike more frequently throughout the year are particularly good at assessing their own surefootedness and physical performance. However, it was also found that route planning using maps and considering distance and elevation gain are generally not undertaken.

> Mountain hikers were, for the most part, physically fit for the chosen route and completed it with sufficient surefootedness.

24.4 Risk Management Among Indoor Climbers

Indoor climbing has now developed into an independent sport (Fig. 24.7). Two studies have been conducted on this topic. Study I (Mersch et al. 2005) examined the overall risk management of indoor climbers. Study II focused specifically on the core process of belaying (Funk et al. 2012, 2013). The pre-

◘ **Fig. 24.7** Indoor climbing. (Image rights: Lydia Kraus, with kind permission)

sentation of results refers mainly to Study I but refers to Study II for belay device-related aspects.

24.4.1 Behavioural Errors in Indoor Climbing: Overview

The vast majority of people observed climb or belay without error (◘ Fig. 24.8).

However, error rates vary significantly depending on the activity. During lead belaying, the most complex cognitive and technical task in indoor climbing, participants exhibited the highest number of errors (◘ Fig. 24.9).

Inadequate belaying and "excess slack" account for most observed behavioural errors during indoor climbing (◘ Fig. 24.10).

These behavioural errors are well known to the participants, as confirmed by the subsequent survey. It appears, for example, that no connection is made between the concept of "excess slack" and the actual behaviour, i.e. the rope as seen by the belayer.

> The more complex the activity, the more frequently behavioural errors occur. Theoretical knowledge of an error alone is not sufficient to prevent it.

24.4.2 Differences Between Dynamic Belay Devices and Assisted-Braking Belay Devices ("Semi-Automatic" Devices)

When belaying with dynamic belay devices, active braking force must be applied to arrest a falling climber. Typical belay devices include the "Munter hitch" and various tube devices. In contrast, semi-automatic devices largely block independently in the event of a fall (e.g. "Smart", "Click-up", "Grigri"). In Study I, improper handling of the belay device proved to be the most frequent belay-related behavioural error. Study II therefore focused in particular on whether and to what extent semi-automatic devices would provide increased safety.

To avoid conflating errors of differing severity when comparing belay device types, every possible error for each device studied was classified into one of five "error severity" categories (A–E, with A meaning "error leads directly to a fall"). For the comparison between tube devices and semi-automatic devices, only B and C errors were considered, as no A errors occurred. ◘ Figure 24.11 shows that the use of semi-automatic devices results in a significant increase in safety: Significantly fewer behavioural errors occurred with these devices.

While "tube devices" were still the most commonly used belay devices in the 2012

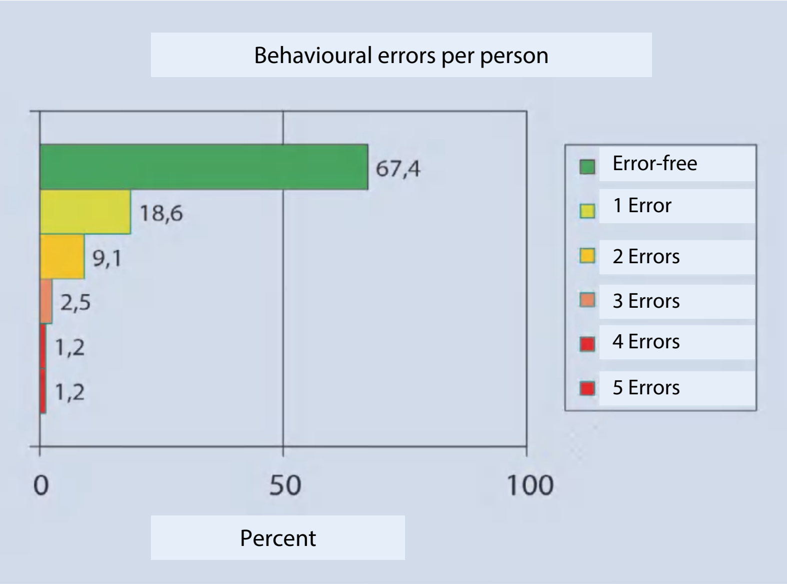


Fig. 24.8 Frequency of behavioural errors per person during indoor climbing. (Image rights: DAV, with kind permission)

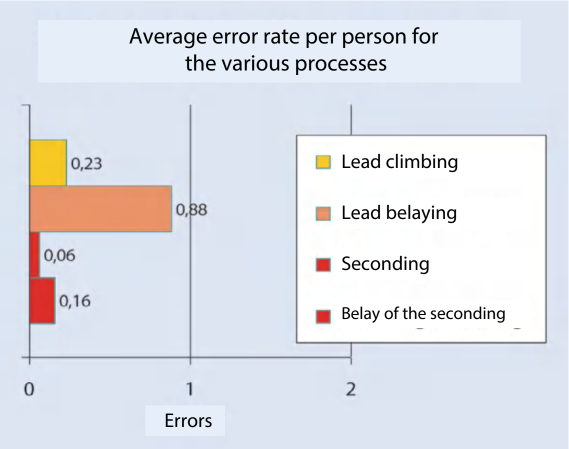


Fig. 24.9 Average behavioural error rates per person, according to different climbing activities. (Image rights: German Alpine Club—DAV, with kind permission)

study, assisted-braking belay devices have now become widely established.

These results do not mean that belaying with dynamic belay devices is negligent. In principle, they can be operated just as safely as semi-automatic devices and, in certain situations, also offer clear advantages (Funk et al. 2013).

Fewer safety-relevant handling errors occur with assisted-braking belay devices than with "dynamic" belay devices.

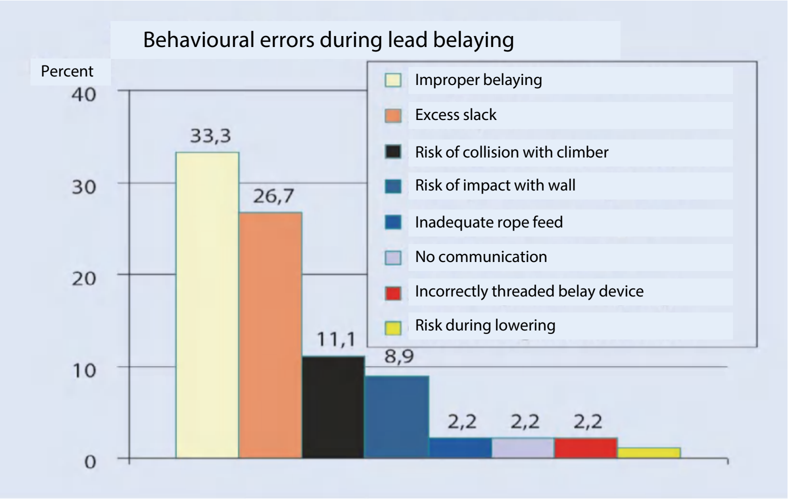


Fig. 24.10 Frequency of different behavioural errors during lead belaying. Note: In no cases were the harness fitted incorrectly. Lead climber falls were rare, and dangerous belaying behaviour during a fall was not observed. (Image rights: DAV, with kind permission)

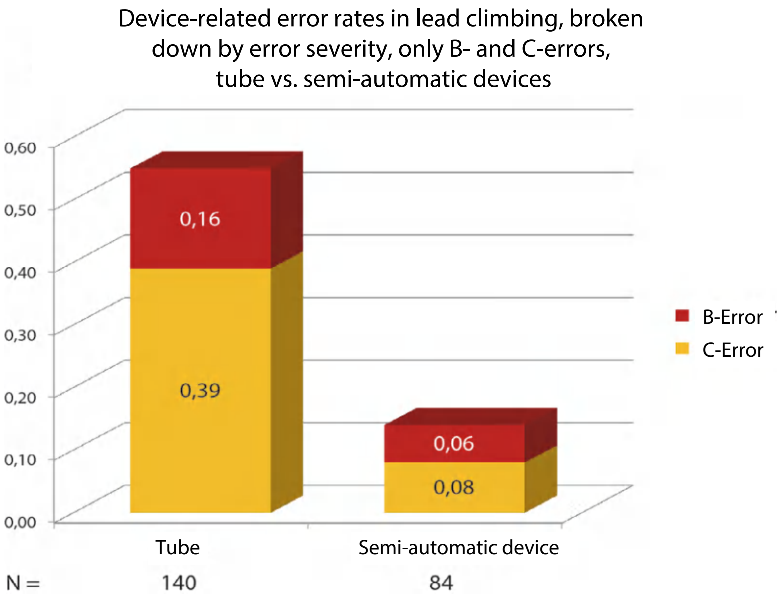


Fig. 24.11 Differences in handling errors between dynamic belay devices (Tube) and semi-automatic devices. No A errors (i.e. leading directly to a fall) occurred. (Image rights: DAV, with kind permission)

24.5 Take Home Message II

The following conclusions can be drawn from the results:

1. Safe behaviour is generally not "put to the test" in the alpine environment. An *unexpected* fall is the exception in indoor climbing. Mountain hikers rarely slip in areas of fall risk, and even with inadequate planning, they usually manage to return to the valley before nightfall.
2. Risk management cannot mean primarily learning from "mistakes", as these may not even be noticed, but must rather mean anticipating errors in planning and in *behavioural experiments*. This is a requirement for training. Specifically, a person learning to belay while climbing must experience and understand what it is like, for example, to have to arrest an unexpected fall at the very moment of changing grip with the belaying hand. Every behavioural concept (such as "no slack rope", "brake hand principle", etc.) should be "stress-tested" during training through behavioural experiments that simulate the worst-case scenario, but of course, with appropriate safety measures in place. Only in this way can knowledge based on experience be developed, along with safe belaying practice. Knowledge without experience remains theoretical; experience without knowledge is uninformed.
3. Where experiential experiments are not possible, *planning scenarios* can be helpful. What if, at this point during the mountain tour, someone were to become exhausted? Good advance planning also enables comparisons between the plan and reality. Are we on schedule? Can we still reach the X col. within the allotted time frame? Crucially, the undertaking is only complete once the debriefing has been concluded.
4. In order to anticipate hazardous situations both during planning and on site, risk management systems are helpful, such as "strategic avalanche awareness" in ski touring, or the "DAV Mountain Hiking Card" (▶ https://www.alpenverein.de/files/2208-bergwandercard-flyer_ol.pdf) in mountain hiking (For English readers please see from Club Arc Alpin ▶ https://www.alpenverein.at/portal_wAssets/docs/bergsport/sicheramberg/cardfolder/Mountain-Hiking-CF-2020-en.pdf). These systems structure perception and lead to a shared mental model among participants, facilitating communication. In both fields, online tools are currently being developed to replace previous analogue aids. It is to be hoped that these will be used more than their analogue predecessors.
5. On site, for example in a climbing gym, there needs to be a supportive *feedback culture*. If someone observes a hazardous situation involving others, they should not hesitate to address it. Those who are approached in this regard should be appreciative of the attention, rather than perceive it as interference.
6. An *attitude of engaged attentiveness* towards the activity in question is beneficial for effective risk management. It is not only about being active, but also about being willing to learn in the process. Mountaineering offers not only beautiful sights, but also insights.
7. Engaged attentiveness is a prerequisite for *safety-related behavioural excellence*. An awkward term, admittedly. But it is not only a pleasure to watch an expert climb, it is also reassuring to know that such a person is in charge of the belay device.

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25 Neurological and Psychiatric Emergencies in the Mountains

Katharina Hüfner and Marika Falla

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25.1 Neurological Emergencies

In German-speaking countries, 25–30% of patients present to emergency departments of central hospitals with acute neurological symptoms. There are no precise data on the incidence of neurological emergencies in alpine or high-altitude medicine; however, review articles and case reports are available (Basnyat et al. 2004; Baumgartner et al. 2007; Wilson et al. 2009). Overall, the spectrum of diseases can be expected to be like that at sea level. The most common key symptoms in neurology are headache, paralysis, and dizziness. These may be caused by a range of benign, but also rare and potentially life-threatening conditions. In this section, we therefore present the most important key symptoms, together with diagnostic approaches, differential diagnoses, and emergency management strategies that are practical in alpine and high-altitude settings. In addition, some important neurological emergencies such as "stroke" or "epileptic seizure" are discussed in dedicated sections. Acute mountain sickness (AMS; ▶ Chap. 7) and high-altitude cerebral oedema (HACE; ▶ Chap. 8) are, by their nature, also associated with neurological symptoms.

It is always important to distinguish whether there is a recurrence or worsening of a pre-existing condition prior to altitude exposure (e.g. migraine, epilepsy), or whether new symptoms have developed. Mountaineering with pre-existing neurological conditions is discussed in ▶ Chap. 21. In cases of doubt, any symptom at altitude should, until proven otherwise, be considered altitude related or associated with altitude illness.

In neurology, initial diagnostic assessment can typically be performed effectively through a clinical neurological examination. This requires proficiency in the basic techniques of the clinical neurological examination: assessing conscious level, signs of meningeal irritation, cognition, cranial nerves, motor function, reflexes, sensation, coordination, and posture/gait.

Two simple measures to remember are as follows: In the presence of focal neurological deficits, blood glucose should always be checked, or if this is not possible, glucose should be administered. In suspected raised intracranial pressure, elevating the upper body (15–30°) with the head in a neutral position should be performed, if possible, for pathophysiological reasons (Rangel-Castilla et al. 2008).

25.1.1 Principal Neurological Symptom: Headache

Headache is a very common symptom, especially in alpine and high-altitude medicine. Up to 90% of people ascending to high altitudes report headaches (Burtscher 1999; Silber et al. 2003). In primary headache disorders, the pain itself constitutes the disease (e.g. migraine), whereas in secondary headache, the pain is a symptom of another underlying condition (meningitis, hypertensive crisis, acute glaucoma (▶ Sect. 45.2.2), sinus infection, dehydration, or altitude).

There is considerable overlap in the diagnostic criteria for migraine, high-altitude headache (HAH), and AMS (Davis et al. 2016). For practical reasons, we recommend that any headache occurring at altitude and meeting the criteria for AMS should primarily be considered and treated as such, since misdiagnosing AMS as migraine could lead to further ascent and potentially to progression to HACE (Karle 3rd and Auerbach 2014). Migraine attacks at altitude may change their characteristics (Murdoch 1995), so that patients may not recognise them as their "usual" migraine. It also remains unclear whether patients with migraine are at increased risk for AMS and/or HACE (Canoui-Poitrine et al. 2014).

> To reiterate, any symptoms occurring at altitude and fulfilling the criteria for AMS should primarily be regarded as such, since the diagnostic criteria for headache in AMS overlap with those for migraine and high-altitude headache.

25.1.1.1 Migraine (Primary Headache)

Migraine can be triggered by altitude (probably due to hypoxia) (Britze et al. 2017), and patients with a history of migraine are generally prone to developing headaches at altitude (Davis et al. 2016). Migraine is typically characterised by unilateral, pulsating headache, moderate to severe intensity, and aggravation by routine physical activity (e.g. walking or climbing stairs). During the headache, nausea with or without vomiting, or photophobia and phonophobia must be present (Headache Classification Committee of the International Headache Society 2018). A typical feature of migraine is the aura that occurs within 60 min of the onset of headache. It may precede or accompany the headache but does not occur in all patients or with every attack. The aura consists of focal neurological symptoms that develop gradually (over ≥5 min) and last between 5 and 60 min. Visual symptoms (flashes or flickering) or sensory disturbances are most common. All patients with migraine should be informed that their condition may worsen at altitude, both in frequency and intensity. Migraine patients should carry medication that is familiar to them and effective. The use of triptans at altitude is considered safe and may be used by patients who normally take them for migraine attacks, provided there are no other contraindications. Triptans may also be effective in the prevention of AMS (Jafarian et al. 2007). Whether triptans are also effective against high-altitude headache is unclear (Burtscher et al. 1995). Acetylsalicylic acid should not be used due to the risk of bleeding in the presence of comorbidities or injuries.

1. Treatment of acute migraine attack (German Society of Neurology (DGN) Guidelines): Metoclopramide 10–20 mg orally or intravenously plus 400 mg ibuprofen
   - Second-line option: 1 g paracetamol when NSAIDs are contraindicated
   - Triptans, if patients normally use these for migraine attacks

25.1.1.2 Tension-Type Headache (Primary Headache)

This is the most common type of headache, experienced by almost everyone at some point in life. Lifetime prevalence is up to 80% (Headache Classification Committee of the International Headache Society 2018). The pain is typically bilateral and of an oppressive, constricting quality. It is of mild to moderate intensity and is not aggravated by routine physical activity. There is no associated nausea (Headache Classification Committee of the International Headache Society 2018). The presence of focal neurological signs or severe comorbid medical conditions or symptoms makes this diagnosis less likely, and an underlying cause should be sought. The duration of an episode can be up to 1 week.

Treatment of acute tension-type headache (German Society of Neurology (DGN) Guidelines), e.g.:

- 500–1000 mg paracetamol orally or
- 200–400 mg ibuprofen orally

25.1.1.3 Headache Associated with AMS/HACE (Secondary Headache)

► Chapters 7 and 8.

25.1.1.4 High-Altitude Headache (Secondary Headache)

More than 30% of individuals ascending to high altitudes (>2500 m) experience high-altitude headache (Burtscher et al. 2011). This is typically a bilateral, dull headache of pressing quality and mild to moderate intensity, which may also exhibit features of migraine headache (Broessner et al. 2016). High-altitude headache worsens with increasing altitude, exertion, movement, straining, coughing, or bending over and resolves within 24 h after descent (Headache Classification Committee of the International Headache Society 2018). Non-pharmacological measures are the same as those for the prevention and treatment of AMS (▶ Chaps. 7 and 8):

- Prophylaxis of high-altitude headache (Xiong et al. 2017; Gertsch et al. 2010): 400–600 mg ibuprofen three times daily or 85 mg acetazolamide three times daily
- Treatment of high-altitude headache (Harris et al. 2003): 400–600 mg ibuprofen or 1 g paracetamol or 10 mg metoclopramide (Irons et al. 2020)

It is important to note that, on the one hand, treating high-altitude headache by reducing headache symptoms may mask the onset of AMS, while, on the other hand, gastrointestinal side effects of ibuprofen may be mistaken for AMS symptoms.

25.1.2 Principal Neurological Symptom: Vertigo and Dizziness

Patients complain of vertigo, dizziness, and lightheadedness frequently. It is particularly important to differentiate what sensation the patient is referring to: Is it a presyncopal sensation in the context of dehydration and low blood pressure—“lightheadedness”, a general feeling of malaise due to poor sleep or disorientation—“dizziness”, or rotational or oscillatory sensation of the world around the person or the person itself—vertigo? Vertigo is often accompanied by autonomic symptoms such as vomiting. If, in addition to vertigo or dizziness, other focal neurological signs are present, a central lesion should be considered.

As with headache, the problem is that vertigo and dizziness are symptoms of AMS. If they occur at altitude in conjunction with headache, they should always be primarily regarded as a sign of AMS. In principle, diagnostic clarification and specific therapy should be sought. Symptomatic treatment may include, for example, 50 mg dimenhydrinate by mouth. (It is also available as a suppository or i.v.) or 4–8 mg ondansetron (oral or i.v.). Use should be limited to a few days. The sedative effect of dimenhydrinate should be considered in the alpine medicine setting.

25.1.2.1 Benign Peripheral Paroxysmal Positional Vertigo

A very common cause of vertigo is benign peripheral positional vertigo, which may occur post-traumatically or spontaneously. This is caused by dislodged otolith crystals moving within the semicircular canals. This type of vertigo is in itself harmless, but during changes in head or body position, it leads to brief attacks without focal neurological symptoms, which may pose a risk during climbing or mountaineering. Diagnosis and treatment are clinical and can be easily performed in alpine or high-altitude medicine. During positional manoeuvres, vertigo can be triggered and nystagmus observed, which subsides within seconds to minutes (German Society of Neurology (DGN) Guidelines).

25.1.2.2 Vestibular Neuritis

This is a viral inflammation of the vestibular nerve presenting as isolated vertigo without hearing loss, lasting for several days. As it is likely due to reactivation of latent herpes viruses, an increased incidence at altitude is to be expected. Clinically, a horizontal rotatory nystagmus is observed. Improvement can be achieved with 100 mg methylprednisolone per day with gastric protection followed by a tapering dose—reduce daily dose by 20 mg every fourth day (German Society of Neurology (DGN) Guidelines).

25.1.2.3 Ménière's Disease

Due to pressure differences at altitude, the occurrence of Ménière's disease may be more frequent at altitude (Gurkov et al. 2016). This condition is characterised by vertigo attacks lasting for hours, accompanied by hearing loss, ear pressure, and tinnitus. As it is a chronic disease, most patients are usually already aware of their diagnosis before embarking on a tour. Acute management is symptomatic.

25.1.3 Principal Neurological Symptom: Paralysis and/or Sensory Disturbance

In cases of paralysis and/or sensory disturbances, it is always important to first perform a topographical diagnosis: a peripheral lesion is generally less serious (although it can still lead to dangerous impairment in the mountains), whereas central lesions indicate a process in the brain or spinal cord and usually require urgent intervention. Clues to a central lesion in the acute phase include, for example, preserved forehead movement (forehead wrinkling) in facial palsy or a positive Babinski reflex. Further signs of a central origin, which may develop over time, include increased muscle tone, spasticity, and hyperreflexia in the affected limb. Additional neurological deficits such as diplopia or dysarthria also suggest a central cause. In contrast, peripheral paralysis and sensory disturbances are characterised by their distribution within the territory of a nerve root or peripheral nerve. This section presents important peripheral causes; in the case of a suspected central origin, in addition to HACE, stroke should also be considered.

> Numbness or paralysis in alpine/high-altitude medicine is often due to compression injuries of peripheral nerves caused by unfamiliar physical strain or the sleeping conditions in the mountains.

25.1.3.1 Intervertebral Disc Lesion

Intervertebral disc herniations most commonly occur in the lumbar spine (LWS) region. Depending on the site of the herniation, this may result in a nerve root lesion or spinal canal compression. Disc herniation is frequently associated with back pain, paravertebral muscle tension, tenderness or pain on percussion over the spine, pain on coughing, straining, or sneezing, and clinically positive nerve stretch signs. A neurological emergency exists if there is less than three-fifths paresis (movement against gravity still possible) or if there are bladder or bowel disturbances. Even milder cases can, of course, adversely affect the course of a tour.

Management of acute intervertebral disc herniation (German Society of Neurology (DGN) Guidelines):

- Analgesia: Paracetamol 500–1000 mg, or ibuprofen 400–600 mg, or tramadol 100–200 mg, or other opioids (noting known side effects)
- Depending on symptom severity, additionally muscle relaxants such as tizanidine or, if unavailable, benzodiazepines (caution should be made and increased vigilance due to the known respiratory depression and sedation side effects; see ► Sect. 25.2.8)
- If symptoms are very severe, possibly also 50–100 mg prednisolone per day (evidence lacking)

25.1.3.2 Peripheral Nerve Lesions

These are probably the most common causes of paralysis and sensory disturbances in alpine/high-altitude medicine. Paralysis and sensory disturbances usually occur simultaneously within the distribution of a nerve or nerve plexus (◘ Table 25.1). This is related to unfamiliar physical strain, clothing/equipment, and sleeping conditions, which can cause compression injuries.

Pressure relief is advisable and, if necessary, splinting or taping to compensate for the affected function. In addition, nocturnal immobilisation in a neutral position and padding can support nerve recovery. Further pressure lesions and strain should be strictly avoided. In carpal tunnel syndrome, a trial of oral prednisolone 20 mg in the morning or local infiltration of 60 mg methylprednisolone into the carpal tunnel may be considered (German Society of Neurology (DGN) Guidelines).

25.1.3.3 Polyradiculitis

This primarily refers to Guillain-Barré syndrome, which can occur spontaneously but especially after infections. It is a common cause of symmetrical, flaccid paresis with areflexia; sensory disturbances, pain, and autonomic dysfunction may also occur. Reduced vital capacity and cardiac arrhythmias may necessitate intensive care, so autonomic functions should be monitored and the patient should be rapidly evacuated as a priority. Acute management in the context of alpine/high-altitude medicine is purely supportive.

25.1.3.4 Peripheral Facial Palsy and Other Cranial Nerve Palsies

Peripheral facial palsy is clearly distinguished from central lesions by the involvement of all three facial branches; in contrast, in a palsy from a central lesion, the frontal branch is spared due to its bilateral innervation. Peripheral facial palsy is treated with

Table 25.1 Important peripheral nerve lesions due to compression

Affected nerve	**Location**	**Symptoms**
Long thoracic nerve	In the region of the clavicle/first rib due to pressure from rucksack straps	Rucksack palsy: the arm can no longer be raised above the horizontal, and the scapula protrudes dorsally (scapula alata)
Median nerve	Carpal tunnel at the level of the carpal bones, often due to increased repetitive movements	Brachialgia paraesthetica nocturna: tingling or needle-like paresthesias in the affected hand, predominantly in the palmar aspect of digits I–III, impaired thumb abduction Symptoms typically occur at night or when the hand is held in a fixed flexed or extended position and improve with shaking of the hand
Ulnar nerve	In the region of the ulnar sulcus	Radiating pain to the fourth and fifth fingers; sensory disturbances of these two fingers both palmar and dorsal, claw hand, impaired thumb adduction, and finger spreading
Radial nerve	In the upper arm after sleeping on a hard surface ("park bench lesion")	Wrist drop due to paresis of the wrist extensors with sensory disturbances on the dorsum of the hand and dorsal forearm
Fibular nerve	At the level of the fibular head	Steppage gait (foot drop) due to paresis of the toe and foot extensors, sensory disturbance of the adjacent surfaces of the first and second toes, sometimes involving the entire dorsum of the foot

Simplified overview according to Berlit (2014) corticosteroids, e.g. 60 mg prednisolone in the morning for 5 days, then daily reduction by 10 mg, or alternatively prednisolone 25 mg twice daily for 10 days with gastric protection; the use of antivirals is controversial and, therefore, not routinely recommended except in cases suggestive of herpes zoster infection (German Society of Neurology (DGN) Guidelines; Diener et al. 2017). Other cranial nerve palsies may also occur with high-altitude exposure (Wilson et al. 2009). For example, sixth cranial nerve (abducens nerve) involvement is relatively common at altitude, although the cause usually remains unclear and the condition is generally benign (Basnyat et al. 2004; Falla et al. 2021a, b, c). However, raised intracranial pressure, for example, in the context of HACE, may also be the cause. These cases constitute a medical emergency.

25.1.4 Principal Neurological Symptom: Disturbance of Consciousness and Cognition

Disorders of consciousness and cognition may have a wide range of internal medicine, psychiatric, and neurological causes. At high altitude, altitude-related causes such as HACE should be considered first. Quantitative disturbances of consciousness are, for example, assessed using the Glasgow Coma Scale, while qualitative disturbances include confusional syndromes in delirium, for which there are also assessment scales (e.g. Delirium Observation Scale). Internal medicine causes of disturbances of consciousness include, for example, syncope, hypoglycaemia, and other metabolic disorders (► Sect. 21.3), while psychiatric causes include delirium, intoxication, or hyperventilation in the context of a panic attack (► Sect. 25.2). Neurological causes for disturbances of consciousness, include stroke (haemorrhagic and ischaemic), epilepsy including postictal states, and traumatic brain injury (► Sect. 26.3). Strokes particularly lead to loss of consciousness when the posterior circulation and thus the brainstem are affected. Other brainstem signs include the "D's" such as Dysarthria, Diplopia (with ocular motor disturbances), and Dysphagia. In transient global amnesia (Litch and Bishop 1999), there are qualitative disturbances of consciousness with disorientation in place and time (but not person); the state is characterised by confusion and uncertainty, although purposeful actions (e.g. train travel) may still be carried out. Retrospectively, there is an amnestic gap (retrograde amnesia). During the episode, the patient repeatedly asks stereotyped questions and is unable to retain new information (anterograde amnesia). Pathophysiologically, a hypoperfusion of the hippocampus is assumed. The condition resolves completely within 24 h at the latest (German Society of Neurology (DGN) Guidelines). Cognitive impairments (e.g. attention, concentration, memory, or executive functions) may occur in internal medicine conditions (e.g. infection), psychiatric (e.g. delirium; ► Sect. 25.2.4), or neurological (e.g. stroke) disorders. However, altitude exposure itself, even in the absence of other symptoms, can lead to cognitive impairment, with the extent of impairment closely related to the degree of hypoxaemia (McMorris et al. 2017). Different cognitive domains are affected by varying degrees by altitude exposure, with considerable variability between studies (Bliemsrieder et al. 2022). In particular, there may be slowing of reaction times, impaired attention, and deficits in working memory (Falla et al. 2021a, b, c, 2022). Altered risk-taking behaviour may also occur (Pighin et al. 2022). Cognitive impairment at altitude, even if it occurs in isolation, can pose a health risk, as it may lead to accidents. Furthermore, sleep deprivation and cold, which are particularly common at altitude, may further worsen cognitive function (Falla et al. 2021a, b, c).

To reiterate its importance, HACE should always be considered first when a disturbance of consciousness or cognitive impairment occurs at altitude. Nevertheless, internal medicine causes such as syncope or hypoglycaemia and psychiatric causes such as intoxication or delirium are probably more common in alpine/high-altitude medicine than primary neurological aetiologies.

25.1.5 Stroke

Stroke can be due to cerebral ischaemia and intracerebral haemorrhage. Clinical differentiation between these two conditions, which have different therapeutic implications, is not possible without imaging. In a "normal" population sample, ischaemic strokes account for approximately 85% of all cases, intracerebral haemorrhages for 10–15%, subarachnoid haemorrhages for about 5%, and cerebral venous thromboses for about 1% (German Society of Neurology (DGN) Guidelines). Headache is not a typical symptom of stroke but may occur in cases of dissection of cerebral vessels, subarachnoid haemorrhage, or cerebral venous thrombosis. The risk of stroke is probably increased at high altitude (Baumgartner et al. 2007). Factors such as polycythaemia, haemoconcentration, impairment of cerebral vascular autoregulation, cardiac arrhythmias, and endothelial damage may contribute to this risk, although it remains unclear whether hypobaric hypoxia truly induces a prothrombotic state (Woods et al. 2008; Richalet et al. 1991; van Veen and Makris 2008).

Ischaemic strokes and intracranial haemorrhages may occur in association with HACE. In individual cases, HACE may initially present as a "stroke" (Yanamandra et al. 2014).

Several algorithms for the rapid diagnosis of stroke by non-medical or non-neurological personnel have been published. The more complex the algorithm, the more accurate it tends to be in detection, but the more difficult it is to apply. The FAST algorithm (▣ Table 25.2) has also proven effective for medical non-physician personnel such as paramedics (Harbison et al. 2003). A significant disadvantage is that strokes in the posterior circulation (i.e. brainstem and cerebellum) are not well detected.

25.1.5.1 Cerebral Ischaemia

In a transient ischaemic attack (TIA), symptoms resolve within 24 h, whereas in cerebral ischaemia, symptoms persist beyond this period.

The acute medical challenge is to distinguish an ischaemic stroke from a haemorrhage. This is difficult or impossible without cerebral imaging. A possible alternative could be a portable ultrasound device, which may be helpful in therapeutic decision-making at least in cases of large vessel occlusion (Wilson et al. 2011). A stroke due to paradoxical embolism should be considered in the presence of deep vein thrombosis, as increased pulmonary vascular resistance and arterial pressure resulting from hypoxic vasoconstriction at high altitude increase the likelihood of a right-to-left shunt in individuals with a patent foramen ovale (30% of the healthy population). The gold standard therapies

▣ **Table 25.2** FAST algorithm (National Stroke Association U.K.)

F	Face: ask the person to smile Does one side of the face droop? Is the face asymmetric?
A	Arms: ask the person to raise both arms Does one arm drift down involuntarily?
S	Speech: ask the person to repeat a simple sentence Is their speech slurred or incoherent?
T	Time: act immediately

(thrombolysis, mechanical thrombectomy) will only be available in a few locations at altitude and usually not within the thrombolysis time window. In suspected stroke, rapid evacuation is always indicated, and a hospital with imaging facilities, ideally with a stroke unit, should be sought. Without imaging to differentiate between haemorrhage and ischaemia, meaningful therapy is not possible. Therefore, no recommendation can be made for therapy with aspirin. As this constitutes early secondary prevention rather than treatment of the acute event, it can only be initiated after exclusion of haemorrhage. Emergency management in suspected ischaemic stroke consists of oxygen administration (as reduced oxygen saturation can generally be assumed at altitude) and elevating the upper body to 30°. Blood pressure should not be lowered abruptly in suspected ischaemic stroke. Systolic values above 220 mmHg and diastolic values above 120 mmHg should be reduced slowly, as should fever and blood glucose levels above 200 mg/dl (German Society of Neurology (DGN) Guidelines).

After a TIA, there is a significantly increased risk of stroke or other cardiovascular events. A particular feature of TIA is amaurosis fugax, a transient monocular blindness due to retinal ischaemia. Following a TIA, there is a high risk of ischaemic stroke or other cardiovascular events in the subsequent hours or days, so this should also be regarded as an emergency. Mountaineers who have experienced a TIA without sequelae should undergo thorough evaluation at home (Blasco Mariño et al. 2023; Richalet et al. 2020).

25.1.5.2 Intracerebral Haemorrhage

Suspicion of an intracerebral haemorrhage arises particularly in anticoagulated patients (warfarin or direct inhibitors). Vascular malformations, amyloid angiopathy, or extremely elevated blood pressure are predisposing factors. Emergency management in the mountains, when intracerebral haemorrhage is suspected, consists of administering oxygen, elevating the upper body by 30°, and lowering blood pressure to achieve systolic values at or below 140 mmHg, but not below 110 mmHg (German Society of Neurology (DGN) Guidelines). High-altitude exposure may represent a risk factor for intracranial haemorrhage, although it is unclear after what duration of stay this applies (Fang et al. 2011).

> Differentiation between cerebral ischaemia and intracerebral haemorrhage is not possible in the mountains if imaging is unavailable, thus precluding specific therapy.

25.1.5.3 Subarachnoid Haemorrhage

The cardinal symptom is a very severe headache—“unlike any before, a thunderclap headache”. It is often accompanied by signs of meningeal irritation and possibly subsequent reduced consciousness, which can make it hard to differentiate from HACE. A subarachnoid haemorrhage usually results from rupture of an intracranial aneurysm and often affects younger patients. Risk factors for rupture include hypertension, physical exertion (e.g. sexual activity), straining during defecation, and occasionally coughing or sneezing. Subarachnoid haemorrhage is a neurological emergency, as it may lead to recurrent bleeding, hydrocephalus, and vasospasm with subsequent infarction. Rapid evacuation should be sought. Whether high-altitude exposure, with its altered haemodynamics (increased blood flow and capillary permeability), predisposes to subarachnoid haemorrhage is unclear. It is possible that at altitude, the risk of rupture is also increased for smaller aneurysms that are otherwise unlikely to rupture (Cui et al. 2014). This should be considered when individuals with known intracerebral aneurysms plan to ascend to high altitudes. Emergency management in the mountains includes oxygen administration, 30° upper body elevation, and reduction of arterial blood pressure until definitive aneurysm treatment is performed. A target mean arterial pressure of 60–90 mmHg is recommended (German Society of Neurology (DGN) Guidelines).

25.1.5.4 Cerebral Venous Sinus Thrombosis

At altitude, the risk of thrombosis is likely to be increased due to polycythaemia, dehydration, and possibly corticosteroid use. Individuals with pre-existing coagulation disorders, such as protein S or C deficiency or APC resistance (Zavanone et al. 2017), smokers, and women taking hormonal contraceptives are particularly at risk. Headache is a common symptom, often associated with focal neurological deficits and papilloedema. Epileptic seizures may also occur. The progression is often somewhat less acute than in ischaemic stroke or haemorrhage. Without imaging, a definitive diagnosis is not possible. However, once the diagnosis is made, the treatment consists of anticoagulation with heparin. It is worth considering a diagnosis of cerebral venous sinus thrombosis when neurological symptoms occur immediately after a descent from altitude.

25.1.5.5 Stroke and Chronic High-Altitude Exposure

There are only a few studies on stroke in the context of chronic high-altitude exposure. In contrast to sea level, intracranial haemorrhages may be the most common type of stroke among people living permanently at high altitude (Fang et al. 2011). The incidence of acute ischaemic stroke in people living permanently at altitude compared to those at lower elevations is reported inconsistently in the literature (Zheng et al. 2023; Falla et al. 2021a, b, c).

25.1.6 Epileptic Seizure

A distinction must be made between an acute symptomatic seizure and epilepsy. Seizures occurring in close temporal association with a central nervous system disturbance (such as infection, stroke, traumatic brain injury, hypoglycaemia, or similar) are a sign of cerebral irritation. Epilepsy is characterised by recurrent epileptic seizures. In general, patients with epilepsy are already aware of their condition prior to the expedition and will carry emergency medication. For the issue of mountaineering with epilepsy, see ► Sect. 21.4.2). Whether staying at high altitudes can provoke epileptic seizures remains unclear at present (Mieske et al. 2010). In general, a distinction must be made between generalised (usually tonic-clonic) seizures and focal seizures. Epileptic seizures typically last no longer than 2 min. During this time, the patient is in the ictal state. Many seizures are followed by a postictal phase, which, especially in older adults, can last 24 h or longer. Although the neurons no longer exhibit synchronous excessive discharges during this phase, disturbances of vigilance, speech disorders, paralysis, memory impairment, as well as psychiatric symptoms such as depression or, more rarely, psychotic episodes or aggressive states may occur. Postictal paralysis may necessitate evacuation (so-called Todd's paralysis) if it persists. The typical generalised tonic-clonic seizure is dramatic at the time of occurrence but is usually self-limiting. It is often preceded by an aura, consisting of psychological, cognitive, or sensory sensations. This may be followed by an "initial scream" and then a sudden collapse—with possible injuries or falls. A tonic phase followed by a clonic phase usually occurs. Almost always, tongue biting and involuntary loss of urine and faeces are observed. A self-limiting epileptic seizure cannot and should not be treated acutely, as the risks of medication side effects outweigh the benefits. The patient should be protected from injury, but the mouth should never be forced open, nor should the limbs be restrained. Potential seizure triggers such as sleep deprivation, fever, or alcohol should be avoided as much as possible. Further diagnostic evaluation after descent, including EEG and imaging, is important to determine further management (German Society of Neurology (DGN) Guidelines). If another seizure occurs before descent, treatment with, for example, levetiracetam 1000–2000 mg/day possibly in combination with a low-dose benzodiazepine is possible until the patient is in a more secure environment. In general, benzodiazepines should be avoided as much as possible in alpine/high-altitude medicine due to their side effects (see ► Sect. 25.2.8). However, if an epileptic seizure lasts longer than 5 min or consciousness is not regained between two seizures, treatment is required. Status epilepticus is a life-threatening emergency requiring rapid intervention. In this case, pharmacological intervention is appropriate and necessary. First-line agents for seizure termination are benzodiazepines (German Society of Neurology (DGN) Guidelines). Intravenous lorazepam (0.1 mg/kg, maximum 4 mg per bolus, may be repeated once) is currently recommended as an evidence-based initial therapy, but its need to be refrigerated makes it less practical. Alternatives include other benzodiazepines such as intravenous, intranasal, or intramuscular administration of midazolam (intravenous: 0.2 mg/kg, max. 10 mg per bolus, may be repeated once; intramuscular, intranasal: 10 mg) or intravenous or rectal administration of diazepam (intravenous: 0.15–0.2 mg/kg, max. 10 mg per bolus, may be repeated once; rectal: 0.2–0.5 mg/kg, max. 20 mg per bolus). (For the issues around benzodiazepine use in alpine/high-altitude medicine, see ► Sect. 25.2.8). If benzodiazepines are ineffective, we recommend intravenous therapy with levetiracetam (60 mg/kg, max. 4500 mg, over 10 min) or treatment with valproate is also possible (Valproate 40 mg/kg, max. 3000 mg, over 10 min). The guideline-recommended therapy with phenytoin appears impractical in mountain settings.

25.1.7 Meningitis/Encephalitis

All infectious diseases, including meningitis/encephalitis, have a regionally specific spectrum of pathogens that must always be considered. Clinically, meningitis presents with fever, headache, nausea, sometimes vomiting, neck stiffness (meningism), photophobia, and phonophobia. Additionally, focal neurological signs, epileptic seizures, and disturbances of consciousness occur in encephalitis. The occurrence of dangerous herpes simplex virus (HSV) encephalitis may be facilitated by altitude-induced immunosuppression and/or concomitant corticosteroid use. If suspected, immediate treatment with intravenous aciclovir 10 mg/kg three times daily should be initiated while ensuring adequate hydration (German Society of Neurology (DGN) Guidelines). In bacterial meningoencephalitis, in addition to the pathogens, which vary by country, specific resistance patterns must also be considered, making general empirical therapy recommendations difficult. Common pathogens include *Streptococcus pneumoniae* and*Neisseria meningitidis*. Vaccination should be considered in advance depending on the destination country.

Suggested therapy (adaptation according to the presumed spectrum of pathogens) (German Society of Neurology (DGN) Guidelines):

- Dexamethasone 10 mg four times daily (start before antibiotics) plus ceftriaxone 2 g twice daily and ampicillin 2 g six times daily. In regions with a high prevalence of cephalosporin-resistant pneumococci (or corresponding travel history), treatment should additionally include vancomycin 1 g twice daily (reference value, with therapeutic drug monitoring for optimal dosing) or rifampicin 600 mg once daily.

25.2 Psychiatric Emergencies

Psychiatric disorders have a 12-month prevalence of over 30% in the general population (Möller et al. 2015). Surveys show that individuals with pre-existing psychiatric conditions both participate in alpine sports and spend time at high and extreme altitudes (Hüfner et al. 2022). Psychiatric emergencies can therefore occur both in people with pre-existing psychiatric conditions and de novo in previously mentally healthy individuals because of stress and/or altitude exposure. Psychiatric emergencies in the mountains and at high altitude are mostly like those encountered at sea level. It should be borne in mind that, due to the persistent stigma associated with "mental health problems", many patients are likely to emphasise physical symptoms and only report psychological complaints when specifically asked.

The most important psychiatric emergencies are organised here by their principal symptom (psychomotor agitation, anxiety, suicidal ideation); additionally, key clinical syndromes—acute stress reaction, intoxication, delirium, and high-altitude psychosis—are described. For cognitive disorders, see ▶ Sect. 25.1.4; for sleep disorders, see ▶ Chap. 5; and for anxiety disorders, see ▶ Chap. 46. According to the vulnerability-stress model in the pathogenesis of psychiatric disorders, the stress associated with high-altitude exposure (▶ Chap. 46), combined with the stress of physical exertion, sleep deprivation, etc., predisposes to the development of psychiatric symptoms. ▶ Section 25.2.8 provides an overview of the medications which can be used in psychiatric emergencies.

Individuals with a pre-existing psychiatric disorder are at increased risk of developing symptoms of acute mountain sickness when exposed to high altitude (Hüfner et al. 2022). Interestingly, this association also appears to be bidirectional: an individual who has previously been diagnosed with acute mountain sickness has a higher risk of developing a psychiatric disorder in the course of time (Wang et al. 2023). Whether these are purely statistical associations or causal relationships is the subject of current research. The occurrence of acute mountain sickness is associated with anxiety and a tendency towards somatisation prior to high-altitude exposure (Talks et al. 2022; Bian et al. 2016), as well as with the degree of attention towards bodily symptoms (Bärtsch 2022).

In all psychiatric emergencies, it is of great importance that the attending person remains calm, empathetic, assertive and conveys a sense of safety without being coercive. In cases of psychomotor agitation, verbal de-escalation can calm many situations (◘ Table 25.3). It is often helpful to offer something to eat or drink to establish contact with the patient.

A psychiatric assessment serves to establish a psychiatric diagnosis. This involves not only taking the patient and their problems seriously but also determining whether the symptoms are due to an underlying psychiatric disorder. The medical history should include questions about previous psychiatric illnesses, alcohol or drug use, and suicidal ideation. Suicidal ideation should be addressed directly, as this is relieving for those affected and does not trigger suicidal behaviour. The documentation of a psychopathological report should cover the following areas (at a minimum): consciousness including orientation—screening of neurocognitive abilities (e.g. memory: ask the patient to remember three words, recall immediately and after a delay; concentration and attention: serial subtraction of 7 from 100)—formal (thought process) and content-related thought disorders (delusions)—perceptual disturbances (hallucinations)—mood—psychomotor activity and

Table 25.3 Strategies for verbal de-escalation

Recommended behaviour	Practical implementation
Respect personal space	Maintain a distance of two arm's lengths to the patient
Do not be provocative	Do not assert yourself over the patient or stare at them
Establish verbal contact	The person who first meets the patient should coordinate further action
Use precise, simple language	
Identify feelings and wishes	Regardless of whether or not it can be granted, everyone should be asked what their request is
Listen carefully to what the patient has to say	Repeat what has been said in simple terms to ensure understanding. "If I understand you correctly, you want to tell me …"
Agree with the patient or "agree to disagree"	Support the patient where possible, and use generalisations if appropriate, e.g. "Yes, everyone should be treated with respect", "There are other people who would feel the same way as you"
Lay down the law and set clear limits	Inform the patient that violence or verbal abuse will not be tolerated
Offer alternatives and convey optimism	Never deceive the patient or offer something that cannot be provided
Conduct a debriefing with the patient and other staff	

Adapted from Richmond et al. (2012)

autonomic functions—suicidal ideation and risk to others.

25.2.1 Principal Psychiatric Symptom: Psychomotor Agitation

Agitation may be a manifestation of psychiatric or somatic illness and can occur due to various underlying pathologies and in different clinical contexts: in mental disorders secondary to physical illness, such as metabolic disorders or infections; in delirium; and in manic disorders, psychoses, and substance intoxication or withdrawal. In cases of severe motor agitation, patients may endanger themselves and those around them.

The first priority is to ensure the safety of the treating staff (and the surroundings) as well as the patient; in cases of pronounced aggression, as many helpers as possible should be involved. It is advisable to remove potentially dangerous objects and not to remain alone with the patient. Initially, every effort should be made to calm the patient verbally in a quiet environment (verbal de-escalation, see ◘ Table 25.3). If this is not possible, medication should be selected according to clinical symptoms and the presumed cause of agitation. Oral medication should be preferred whenever possible. Coercive measures (e.g. intramuscular medication without the patient's consent) should only be used as a last resort after all other options have been exhausted and in the presence of acute danger. Legal requirements for coercive measures vary by country and situation. The advantage of benzodiazepines is their reversibility with flumazenil, while antipsychotics have the benefit of fewer interactions, especially with other CNS depressants such as alcohol. If psychotic symptoms are present, an antipsychotic should always be administered. The advantages and disadvantages of emergency medications are discussed in ▶ Sect. 25.2.8. It is important to subsequently identify and treat the underlying psychiatric or physical illness.

> In cases of psychomotor agitation, a calm, empathetic, direct, but non-coercive approach is indicated, as many situations can be de-escalated verbally.

25.2.2 Principal Psychiatric Symptom: Suicidal Ideation

Suicidal ideation occurs more frequently in people living at high altitudes than at sea level; however, nothing is known about short-term stays (Reno et al. 2017). It remains unclear whether high altitude (hypoxia) itself predisposes to suicidality or whether other factors, such as poorer healthcare provision—particularly regarding psychiatric disorders—play a role. It is, however, also known that staying at high altitude can trigger depressive symptoms (de Aquino Lemos et al. 2012; Shukitt-Hale et al. 1998). Although little is known about suicides in alpine or high-altitude medicine, it cannot be ruled out that some “accidents” in the mountains are in fact suicides, as is sometimes the case with road traffic accidents.

It is important to directly address if there is suspicion of suicidal ideation. Possible questions for assessing suicidal tendencies, according to Pöldinger (1982), include:

- Have you recently found yourself thinking about ending your own life?
- Have you thought about it without wanting to?
- Do you have specific plans on how you would do it?
- Have you made any preparations?
- Have you ever attempted suicide?
- Do you consider your situation to be hopeless and futile?
- Do you find it difficult to think about anything other than your problems?

Verbal crisis intervention is a priority treatment, and the patient must not be left alone. The administration of benzodiazepines should be considered in severe cases. Self-harming behaviours such as “cutting” or “burning” (non-suicidal self-injury) are usually intended to relieve tension and should not be equated with suicide attempts. They occur most frequently in emotionally unstable personality disorder.

25.2.3 Principal Psychiatric Symptom: Anxiety

Anxiety, both as a normal reaction and as a disorder, is discussed in ▶ Chap. 46. At this point, attention is drawn to the symptomatology of panic attacks, which can be mistaken for acute cardiac or pulmonary illness, especially when physical symptoms such as hyperventilation or chest pain predominate. Panic attacks are not limited to specific situations or circumstances and are, therefore, unpredictable. Key symptoms include sudden onset of palpitations, chest pain or tightness, shortness of breath, dizziness, and feelings of detachment (depersonalisation or derealisation). Hyperventilation during a panic attack can lead to lightheadedness, tingling around the mouth and in the fingers, and contraction of the forearm muscles (“carpopedal spasm”) because of relative hypocalcaemia due to respiratory alkalosis.

Initial treatment includes remaining calm, guiding the patient to breathe slowly, and, if there is no risk of hypoxaemia due to extreme altitude, considering “rebreathing” into a paper bag to increase carbon dioxide levels. Stressful situations in the mountains as well as the hypobaric hypoxic environment can promote the onset of anxiety symptoms (Burtscher et al. 2022).

25.2.4 Delirium

The term “delirium” encompasses entities such as organic psychosyndrome, acute confusional state, delirious/acute confusion, and certain forms of encephalopathy. Delirium is characterised by disturbances of attention, orientation, and consciousness that develop over a short period and typically manifest as significant confusion. Delirium is often accompanied by behavioural and emotional disturbances as well as disruption of the sleep-wake cycle (World Health Organisation 2019/2021). Delirium is marked by an abrupt onset and fluctuations throughout the day, usually worsening at night.

Delirium is always a manifestation of one or more underlying pathologies that must be identified. A distinction must be made between substance-induced delirium due to alcohol or drug intoxication or withdrawal and non-substance-induced delirium. Particularly in delirium caused by withdrawal, life-threatening autonomic dysregulation may occur. The longer a delirium persists, the poorer the cognitive outcome over time.

> Delirium is an aetiologically non-specific organic brain syndrome, characterised by concurrent disturbances of attention, orientation, and consciousness, and typically presents as confusion. In delirium, there is always an underlying cause that must be identified. Delirium at high altitude may be a manifestation of HACE.

25.2.4.1 Substance-Induced Delirium

Delirium most commonly occurs during alcohol withdrawal but may also arise during withdrawal from benzodiazepines or other substances. Delirious symptoms can also occur in the context of intoxication.

The typical alcohol withdrawal syndrome begins 6–8 h after cessation or reduction of alcohol intake (e.g. when individuals who regularly consume alcohol reduce their intake at altitude due to concerns about side effects). The symptomatology includes general hyperactivity, increased anxiety, tremor, sweating, nausea, vomiting, increased sympathetic tone (tachycardia, elevated blood pressure, low-grade fever) (German Society for Psychiatry, Psychotherapy and Psychosomatics Guidelines 2020). Withdrawal seizures typically occur within the first 12–48 h of withdrawal (German Society for Psychiatry, Psychotherapy and Psychosomatics Guidelines 2020).

In the management of alcohol withdrawal, thiamine 100 mg should be administered where possible to prevent Wernicke’s encephalopathy. Otherwise, treatment is based on symptom-guided administration of benzodiazepines. The aim is early intervention to prevent delirium. Clonidine may be added in cases of pronounced autonomic symptoms, although increasing the benzodiazepine dose is generally preferable. In cases of severe delirium and/or marked psychotic symptoms, haloperidol may be given in addition. Severe alcohol withdrawal is often associated with electrolyte disturbances and hypovolaemia, which should also be addressed.

25.2.4.2 Non-substance-Induced Delirium

Symptoms of delirium as a sign of an organic brain dysfunction may indicate HACE at high altitude but can also occur independently of HACE (Basnyat 2002). Infections with fever, dehydration, metabolic derangements such as hyper- or hypoglycaemia, as well as hypoxia, may act as triggers. Among medications, corticosteroids, opioids, antibiotics, and anticholinergic agents are particularly likely to induce delirium. The main risk factors for developing delirium are advanced age and polypharmacy.

In symptomatic treatment, antipsychotics are preferred, as benzodiazepines may worsen the course of non-substance-induced delirium. The most important aspects in managing non-substance-induced delirium are treating the underlying causes (e.g. infection management, rehydration, etc.) and avoiding deliriogenic medications.

25.2.5 Substance Intoxication

Intoxications with alcohol or benzodiazepines are most observed, but intoxication with other substances, such as stimulants used for performance enhancement, is also possible due to the high prevalence of misuse and dependence in the general population. There is evidence from studies that a wide range of medications and substances are misused in the mountains (Robach et al. 2016).

In cases of acute intoxication, securing vital functions and protecting the patient from injury (e.g. falls) are the primary priorities. If the patient is agitated or aggressive, management should follow the approach described in ► Sect. 25.2.1 for acute psychomotor agitation. It should be borne in mind that the sedative effects of medications and the intoxicating substance (especially alcohol or benzodiazepines) may be additive.

> Substance intoxications with legal and illegal medications and drugs, as well as alcohol, are common and should always be considered as a differential diagnosis, including in the mountain environment.

25.2.6 High-Altitude Psychosis

Psychotic symptoms such as hallucinations, delusions, and disorganised speech/thoughts may, for example, be a manifestation of delirium (► Sect. 25.2.4) or an affective disorder (◘ Fig. 25.1), but may also occur in isolation at high altitude, without other physical or other mental symptoms (e.g. the "third man phenomenon": a person feels that someone is walking ahead or behind them and may sometimes see or hear this person, even though no one is present) (Hüfner et al. 2018). Symptoms of isolated high altitude-induced psychosis resolve upon descent but are associated with an increased incidence of accidents and near-misses. Education about such symptoms should therefore be provided alongside information on somatic altitude-associated symptoms such as AMS, HACE, or HAPE prior to the expedition.

Individuals experiencing symptoms of psychosis must not be left alone, nor should they be trusted to make decisions regarding the course of the tour, as they suffer from impaired reality testing and are unable to accurately assess situations. There are no studies on the use of antipsychotic medication in this context; such drugs are only administered in exceptional cases when a rapid descent is not possible. De-escalation of the situation through reality testing, for example, by a tour partner, should be attempted first.

25.2.7 Acute Stress Reaction and Prevention of Post-traumatic Stress Disorder Following Trauma

A psychological trauma is the experience of an event in which one's own life, health, or physical integrity is threatened, or witnessing such an event as it occurs to others. The sense of helplessness experienced during the event is considered the pathogenetic mechanism. Not all individuals exposed to the same stressor develop a mental disorder; this depends on individual predisposition and available coping strategies.

Immediately after the event, an acute stress reaction occurs, which may progress

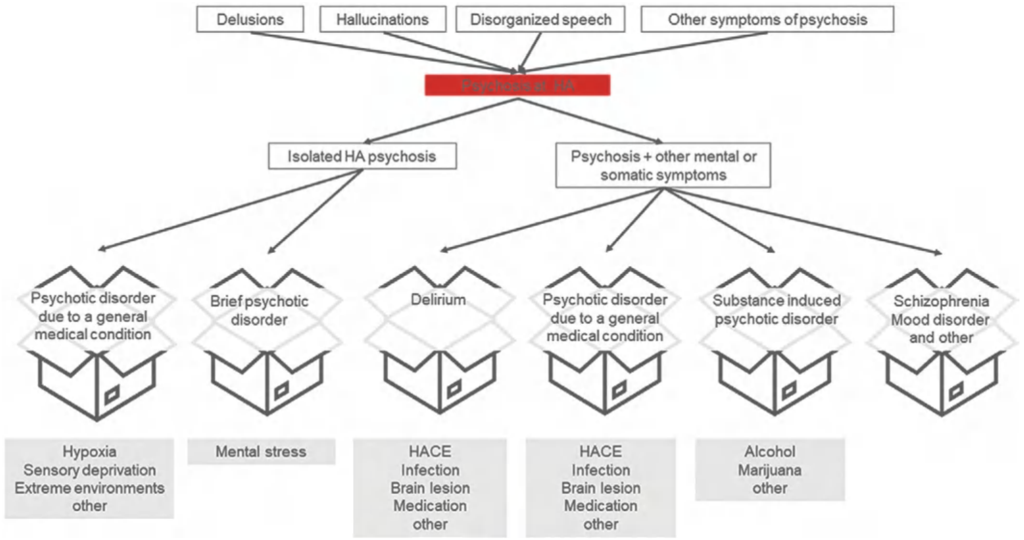
Delusions
Hallucinations
Disorganized speech
Other symptoms of psychosis
Psychosis at HA
Isolated HA psychosis
Psychosis + other mental or somatic symptoms
Psychotic disorder due to a general medical condition
Brief psychotic disorder
Delirium
Psychotic disorder due to a general medical condition
Substance induced psychotic disorder
Schizophrenia Mood disorder and other
Hypoxia Sensory deprivation Extreme environments other
Mental stress
HACE Infection Brain lesion Medication other
HACE Infection Brain lesion Medication other
Alcohol Marijuana other

Fig. 25.1 Psychotic symptoms at high altitude are transdiagnostic, i.e. they may be manifestations of various disorders, and an aetiological classification is essential. *HACE* high-altitude cerebral oedema; *HA* high altitude. (From Hüfner et al. 2023)

to post-traumatic stress disorder (PTSD) if symptoms persist for weeks or re-emerge after weeks or months. The acute stress reaction is a transient syndrome, lasting from hours to a few days after the event. The clinical picture is mixed and typically fluctuates; following an initial state of “numbness”, depression, anxiety, anger (sometimes with aggression), guilt, overactivity, withdrawal, and even dissociative symptoms may be observed. Amnesia for the episode may occur. Autonomic symptoms such as sleep disturbances, tachycardia, and sweating are common (World Health Organisation 2019/2021).

Acute crisis intervention involves removing the affected person from the traumatic situation and bringing them to a calm, sheltered environment, not leaving them alone, and offering supportive conversations: “You are experiencing a normal reaction to an extraordinary event. Even if the symptoms are frightening, this does not mean that something is wrong with you. In many cases, these symptoms resolve spontaneously” (Klein et al. 2016). Providing a sense of safety and reducing stress are central elements of therapeutic intervention immediately after a traumatic event. A debriefing should not be conducted routinely.

There is currently insufficient evidence to support the use of any medication for the prevention of PTSD following acute trauma (Bertolini et al. 2022). From a practical perspective, in cases of pronounced symptoms and significant distress—particularly given the often-challenging conditions in alpine/high-altitude medicine—short-term therapy with a benzodiazepine may be considered. This should be administered for as brief a period as possible, as prolonged use can lead to dependence. Benzodiazepines may potentially increase the risk of developing PTSD, and symptoms of an acute stress reaction often resolve spontaneously. As an acute stress reaction can develop into PTSD, it is advisable to inform those affected about possible symptoms and to recommend contact addresses or support services in case they might later decide to seek psychological help.

The aim of acute crisis intervention is to alleviate the symptoms of the acute stress reaction and ideally to reduce the risk of developing post-traumatic stress disorder.

Post-traumatic stress disorder does not develop immediately after the traumatic event, but rather after weeks to months; therefore, it is not discussed in detail here in the context of emergency medicine. While experiencing trauma is generally common (approximately 80% of the population), only a much smaller proportion (about 8%) develop PTSD, i.e. not everyone who experiences a traumatic event will develop PTSD. Natural disasters and "fateful" traumatic events carry a lower risk of PTSD than "intentional, human-inflicted trauma" such as sexual violence (Sareen 2017).

Patients with PTSD have a high susceptibility to further mental health disorders such as substance use disorders or depression. The main treatment modality of PTSD is psychotherapy, which should be provided by trained therapists. In the context of alpine/high-altitude medicine, it is important to note that avoidance of situations or places, which are reminders of the traumatic event, is a diagnostic criterion for PTSD. Other symptoms of PTSD include flashbacks (intrusive re-experiencing of the trauma), emotional numbing, and indifference as well as hyperarousal with insomnia, increased startle response, and concentration difficulties (World Health Organisation 2019/2021).

25.2.8 Psychiatric Emergency Medications

This section provides an overview of a selection of acute psychiatric medications that should be carried in mountain or high-altitude settings. Many of the uses described here are off-label. Existing guidelines have been taken into account but have been adapted to the limited resources available in alpine/high-altitude medicine. In our view, it is advisable to carry at least one high-potency antipsychotic and one benzodiazepine. Knowledge of side effects and experience in the use of these drug classes are prerequisites.

Psychiatric emergency medication should include at least one benzodiazepine and one second-generation antipsychotic. Both should be available for parenteral administration.

25.2.8.1 Antipsychotics

The choice of an antipsychotic should be based on the expertise of the treating clinician. It is important to note that only aripiprazole, olanzapine, ziprasidone, and haloperidol are available for intramuscular administration. Haloperidol can in principle be given intravenously, but this should only be done under monitoring conditions due to the risk of cardiac arrhythmias, which is rarely feasible in alpine or high-altitude settings. The use of haloperidol should be avoided as far as possible due to the risk of early and late dyskinesias, which can occur even after a single dose, and preference should be given to a second-generation antipsychotic such as aripiprazole, olanzapine, risperidone, quetiapine, or ziprasidone (Huf et al. 2016; Ostinelli et al. 2017).

In cases of pronounced clinical symptoms, a benzodiazepine may be combined with a high-potency antipsychotic. Olanzapine i.m. must not be combined with i.v. benzodiazepines due to the risk of respiratory depression. A low-potency antipsychotic such as melperone may be used in cases of mild agitation or sleep disturbances when benzodiazepines are contraindicated. In elderly patients, a lower dose should always be chosen, e.g. risperidone 0.5 mg or haloperidol 0.5–1 mg.

Haloperidol

- Typical initial dose in acute treatment: 5–10 mg i.m. or orally (drops/tablet)
- Highly effective, but no longer first-line due to side effects

Aripiprazole

- Typical initial dose in acute treatment: 9.75 mg i.m. or 10 mg orally (tablet)
- Alternative to haloperidol, fewer side effects, but also less evidence for use in emergency settings due to fewer studies
- Special characteristics: non-sedating

Olanzapine

- Typical initial dose in acute treatment: 5–10 mg i.m. or orally (orodispersible tablet/tablet)
- Alternative to haloperidol, fewer side effects, but also less evidence for use in emergency settings due to fewer studies
- Special characteristics: strongly sedating, less suitable for the treatment of delirious symptoms due to anticholinergic side effects

Ziprasidone

- Typical initial dose in acute treatment: 20 mg i.m. or orally (tablet)
- Alternative to haloperidol, fewer side effects, but also less evidence for use in emergency settings due to fewer studies

Risperidone

- Typical initial dose in acute treatment: 2–4 mg orally (orodispersible tablet/tablet)
- Special characteristics: Indicated in non-substance-induced delirium

Quetiapine

- Typical initial dose in acute treatment: 50–100 mg (tablet/prolonged-release tablet)

Melperone

- Typical initial dose in acute treatment: 25–50 mg orally (syrup/tablet)
- Special characteristics: Low-potency antipsychotic; has a sedative effect but is hardly antipsychotic

As we recommend the use of antipsychotics in several instances, we would like to draw attention here to a (rare) side effect, the malignant neuroleptic syndrome. This syndrome is characterised by muscle rigidity and elevated temperature, as well as confusion, autonomic disturbances (sweating, tachycardia, fluctuating blood pressure), and tremor. It is important to discontinue antipsychotics and administer benzodiazepines in mild cases; in more advanced stages, evacuation and intensive care treatment are required.

Other side effects (especially of haloperidol) include acute dystonias and, over time, further extrapyramidal motor side effects. Biperiden should be kept available for the treatment of acute dystonia. Cardiac arrhythmias (particularly QTc prolongation) can be triggered by all antipsychotics mentioned here, with the highest risk associated with intravenous administration of haloperidol. Electrolyte disturbances, which are common at high altitude, further increase the risk of cardiac arrhythmias caused by antipsychotics.

25.2.8.2 Benzodiazepines

In psychiatric emergencies at sea level, diazepam, oxazepam, and lorazepam are frequently used orally (the latter is also available as an orodispersible tablet) or intravenously. ▶ Chapter 46 provides information on the effects and side effects of benzodiazepines in the treatment of anxiety; here, therefore, only a few additional remarks are made.

Although there are differences in elimination and potency, it is assumed that the effects of all benzodiazepines in the body are comparable (Ashton 2007). The use of diazepam at high altitude should be approached with caution due to the risk of accumulation from its active metabolites and possible impairment of ventilatory adaptation (Roggla et al. 1994). Most studies on benzodiazepines at high altitude have been conducted with temazepam for the treatment of sleep disorders (see also ► Chap. 5). Earlier studies considered this to be a relatively safe substance without significant effects on respiration or daytime performance (Nickol et al. 2006; Luks 2008; Mohsenin 2015), although other studies have raised concerns about possible respiratory depression with temazepam (Roggla et al. 2000, as well as with diazepam; Roggla et al. 1994) and hangover effects (for Z-drugs, see (Bouzat et al. 2018)). These discrepancies may be due to differences in the altitude studied and the degree of acclimatisation of the subjects.

In our view, any benzodiazepine medication should be carefully considered, especially at high altitude, where respiratory depression or hangover effects can have catastrophic consequences. The UIAA MedCom also takes a critical view of benzodiazepine use, although its recommendations primarily refer to the use for sleep disorders (Donegani et al. 2016). Although generally well tolerated, benzodiazepines have many side effects that can be problematic in alpine or high-altitude environments. These include cognitive impairment and reduced attention, muscle weakness, respiratory depression, dizziness, nausea, and headache. They may cause paradoxical effects (agitation, excitement, aggression, insomnia) and can lead to dependence (though not after a single dose).

In summary, the administration of benzodiazepines is possible at altitude if there is a clear emergency indication. However, the indication for the use of benzodiazepines for transient sleep disturbances at high altitude is much less clear than for an acute psychiatric emergency, such as severe anxiety or suicidality.

Conclusion

Neurological and psychiatric disorders are common, and therefore basic knowledge of their diagnosis and therapy is important for medical personnel in alpine/high-altitude medicine. High-altitude exposure per se can trigger various neurological and psychiatric conditions, such as high-altitude headache or isolated high-altitude psychosis. Other conditions occur more frequently in these settings due to the specific circumstances of alpine/high-altitude exposure, such as migraine, compression injuries of peripheral nerves, or non-substance-induced delirium.

Neurological and psychiatric emergencies can often be diagnosed through targeted history-taking and clinical examination. Many neurological emergencies (e.g. stroke, encephalitis) or psychiatric emergencies (e.g. acute anxiety, intoxication) can be confounded with symptoms of altitude-related illnesses, such as AMS or HACE. In psychiatric emergencies, a calm, empathetic, direct, but non-coercive approach is recommended, which can verbally de-escalate many situations.

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Traumatology in the Mountains

Simon Euler

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26.1 Trauma in Mountainous Terrain

Practical strategies for patient care in mountainous environments differ fundamentally from those in urban and easily accessible areas. Time of day and prevailing weather conditions play a paramount role. With few exceptions, the mountainous region is, in favourable weather and daylight, adequately—often even extensively—covered by a highly developed helicopter rescue system. If darkness and/or adverse weather conditions prevent aerial rescue, there may be significant delays in reaching the patient, and in extreme cases, it may be impossible to access the incident site at all. Additional local hazards such as risk of falling, rockfall, avalanches, or exposure to weather can quickly become life-threatening not only for patients but also for rescue personnel. Hypothermia plays a particularly critical role, affecting both patients and rescuers sooner or later, even in warm ambient temperatures.

Accordingly, the management of trauma patients in mountainous environments often follows less of a theoretically idealised guideline than a pathway adapted to the individual situation and its practical feasibility. Against this background, the following chapter aims to provide a practical overview of the most important and common injuries and their potential management in the mountain environment.

26.2 Epidemiology

With a 10 year average of 7777 police-recorded mountain injuries per year in Austria, trauma in mountainous environments represents a significant issue (Austrian Board for Mountain Safety 2025). Although the relative proportion of injuries compared to the number of people active in mountainous areas has steadily decreased in recent years, the absolute number of injuries continues to rise (with the exception of the COVID-19 pandemic period). The number of fatalities in the Austrian mountains has remained relatively constant over recent years, averaging 286 per year (Niedermeier et al. 2019; Posch et al. 2020).

26.3 Winter vs. Summer

Approximately two thirds of all injuries occur in winter, with about 77% of these associated with piste skiing. In contrast, around 80% of mountain fatalities occur in summer—about 47% of these during mountaineering or hiking. Cardiovascular events account for approximately 30% of deaths in winter and about 40% in summer.

26.4 Multiple Trauma

If a patient sustains multiple injuries simultaneously, at least one of which—or their combination—is life-threatening, this constitutes multiple trauma. Associated injuries are very common in multiply traumatised patients and should be identified using standard protocols (e.g. cABCDE) wherever possible. In this patient group, mortality increases exponentially with time elapsed between incident and definitive care. As a result, mortality among multiply traumatised patients is particularly high in mountain trauma care. Initial management and evacuation should therefore be carried out as rapidly as possible, utilising all available human and technical resources appropriate to the situation. During transport, multiple traumatised patients must be constantly monitored and reassessed. This includes recording and documenting vital signs, the Glasgow Coma Scale, and careful assessment of the pupils (German Society for Trauma Surgery 2022). Life-threatening injuries that can be managed on site or during transport, such as the development of a tension pneumothorax, must be treated promptly whenever possible (Nast-Kolb et al. 2001). Further details can be found in ► Chap. 27 on mountain multiple trauma.

26.5 Traumatic Brain Injury (TBI)

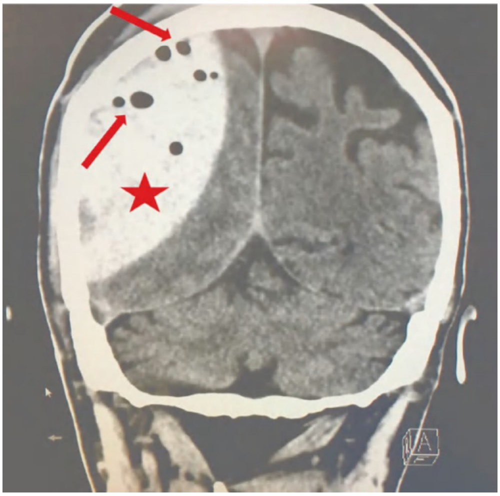
Traumatic brain injury (TBI) plays a major role in mountain trauma care. The coincidence of TBI with other injuries is very high, particularly in multiply injured patients. It is often difficult to accurately determine the stage of TBI in the pre-hospital setting (see classification of TBI in the following overview). However, for subsequent diagnosis and treatment, it is crucial to collect as much information as possible at the outset. A patient with TBI is considered a critical patient and must therefore be rapidly referred for further diagnostic evaluation and therapy. A patient with TBI who appears relatively uninjured immediately after trauma has a high risk of rapid and severe clinical deterioration. For this reason, it is especially important to continuously monitor and assess the patient during transport. As with multiple traumatised patients, this includes regular assessment and documentation of vital signs, the Glasgow Coma Scale (◘ Table 26.1), and careful evaluation of the pupils. Typical symptoms of TBI include (previous) loss of consciousness, amnesia, headache, periorbital or periauricular haematoma, cerebrospinal fluid leakage, nausea, vomiting, and/or dizziness. Ideally, a patient with TBI should be positioned lying down with the upper body slightly elevated. Blood pressure should, if possible, be maintained above 90 mmHg systolic (Chesnut et al. 1993).

At this point, the importance of wearing a helmet should be emphasised once again. Although no helmet can guarantee prevention of severe TBI (◘ Fig. 26.1), it has been

◘ **Table 26.1** Glasgow Coma Scale (GCS)

Domain	**Response**	**Score**
Eye opening	Spontaneous To command To pain None	4 3 2 1
Best motor response	Obeys commands Localizes to pain Withdraws from pain Flexion response Extension response None	6 5 4 3 2 1
Best verbal response	Oriented, appropriate Confused Inappropriate Incomprehensible None	5 4 3 2 1
Maximum score	–	*15*

GCS score 3–8: severe TBI
GCS score 9–12: moderate TBI
GCS score 13–15: mild TBI



◘ **Fig. 26.1** Computed tomography image of a severe intracranial (epidural) haemorrhage *(asterisk)* with air inclusions *(arrows)* repeatedly demonstrated that wearing a helmet during high-risk sports and activities can significantly reduce the risk of head injury, especially in children.

Overview

Classification of Traumatic Brain Injury

Traumatic Brain Injury Grade 1:
- Concussion (commotio cerebri)
- Functional impairment without detectable injury

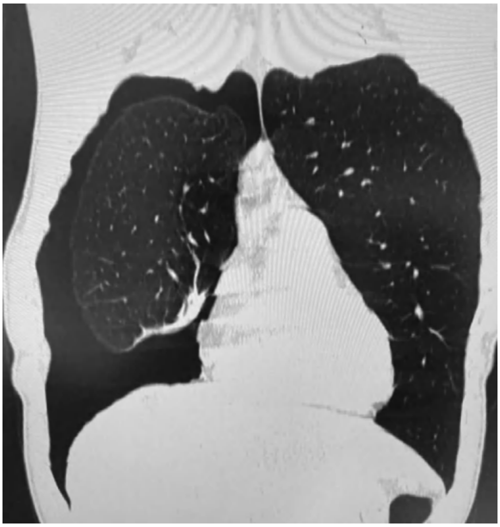
Traumatic Brain Injury Grade 2:
- Mild cerebral contusion (bruise)
- Contusion foci in the brain

Traumatic Brain Injury Grade 3:
- Severe cerebral contusion
- Severe brain injury
- Haemorrhages, prolonged functional impairment

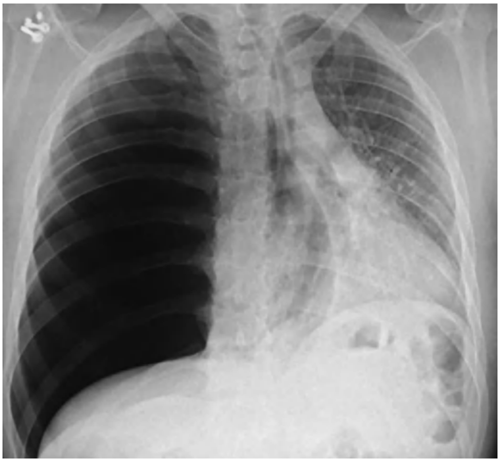
26.6 Thoracic Trauma

Thoracic trauma is particularly common in multiple traumatised patients. This includes bony, cardiac, and pulmonary injuries, or combinations thereof. Seventy percent of all patients with thoracic trauma sustain injuries in other regions of the body, and approximately 25% of all patients suffering severe thoracic trauma do not survive (Rieger et al. 2002).

A pneumothorax occurs when air enters the space between the parietal and visceral pleura (◘ Fig. 26.2). This typically results from penetrating bony injuries. Although most patients with a pneumothorax initially appear to be well compensated, the presence of a valve mechanism may lead to a dangerous increase in the pneumothorax and ultimately to the development of a tension pneumothorax (◘ Fig. 26.3). In this situation, the "air in the wrong compartment" progressively displaces the mediastinum and its organs towards the healthy side, which may result in acute life-threatening compromise and ultimately circulatory failure. Intrathoracic haemorrhages can also exert a mass effect and have similar consequences. Typical symptoms include dyspnoea, pain, hypotension, tachycardia, distended neck veins, and shortness of breath and heart sounds.



◘ **Fig. 26.2** Computed tomography image of a right-sided pneumothorax with collapsed right lung



◘ **Fig. 26.3** X-ray image of a pronounced tension pneumothorax with collapsed right lung and marked mediastinal shift to the left. (Schnell 2023)

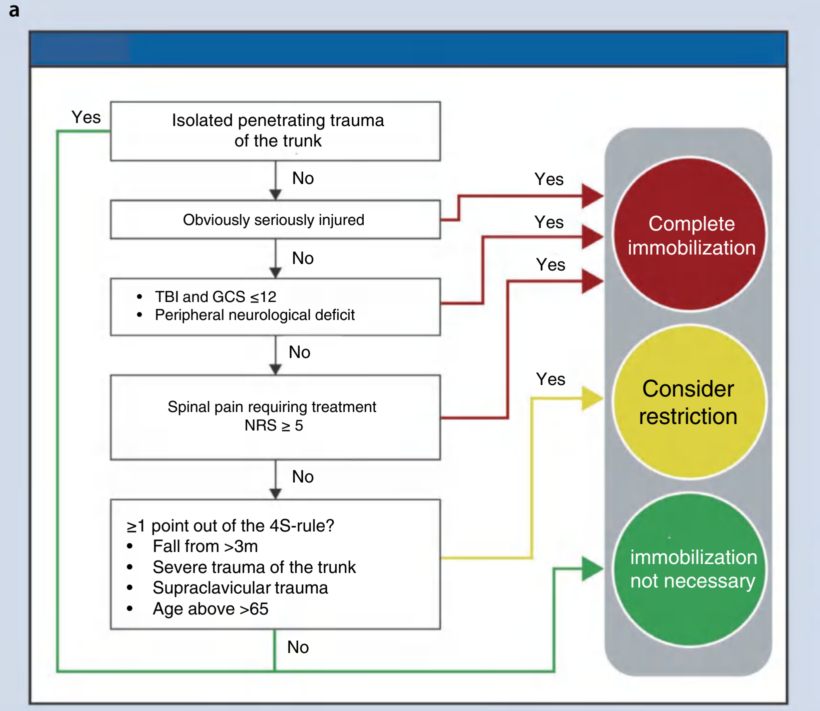
In cases of acute, life-threatening compromise, if in doubt and whenever practically possible, immediate decompression should be performed using mini-thoracotomy and insertion of a chest drain. The access point for the classic and still recommended Bülau drain is at the level of the 4th intercostal space (upper edge of the rib), approximately at the anterior axillary line and (imaginary) level of the nipples. If a chest drain is not available, an endotracheal tube or any other type of tube with a non-collapsible lumen may be used as an alternative. Ideally, in addition to systemic analgesia, local anaesthesia should also be administered. For thoracic trauma, as with other injuries, regular monitoring and (re-) assessment of the patient during transport seem to be essential, as well as, if possible, slight elevation of the upper body.

26.7 Spinal Trauma

The initial management of spinal injuries in alpine environments is highly demanding (◘ Fig. 26.4). Given the long and uneven transport routes, careful positioning of the patient presents a considerable challenge for rescuers.

In general, spinal injuries may occur particularly in cases of falls from great heights or high-velocity trauma. Especially in unconscious patients, if the mechanism of injury suggests it, it is advisable—wherever the situation allows—to immobilise the entire spine as completely and effectively as possible. The lumbar, cervical, and thoracic spine are affected in descending order of frequency. Due to the typically high-energy impact, injuries in other regions of the body are common. The leading symptom is pain. If the patient is awake, an initial and as-precise-as-possible assessment of peripheral neurological deficits is extremely important. Monitoring for any changes in neurological status during positioning and transport is crucial for prognosis and determining the best therapeutic approach.

For many years, the application of a cervical collar to stabilise the cervical spine was considered an undisputed part of standard initial management after any trauma directly or indirectly involving the cervical spine. However, due to questionable immobilisation efficacy of commonly used collars and the frequently observed "over-treatment" with such devices, the absolute necessity of their use is now being critically questioned by some emergency services (Häske et al. 2022). Future research will show where the optimal management lies. However, it is still clear that, in cases of doubt, the application of a cervical collar is strongly recommended.


a
Yes
Isolated penetrating trauma of the trunk
No
Obviously seriously injured
No
• TBI and GCS ≤12
• Peripheral neurological deficit
No
Spinal pain requiring treatment NRS ≥ 5
No
≥1 point out of the 4S-rule?
• Fall from >3m
• Severe trauma of the trunk
• Supraclavicular trauma
• Age above >65
No
Yes
Yes
Yes
Yes
Complete immobilization
Consider restriction
immobilization not necessary

b

The immobilisation traffic light is used for adult patients who can provide information. ABC problems in unstable patients should take priority over immobilisation. For 'yellow' patients, or those with >1 point on the 4S, a thorough explanation should be provided as to why immobilisation was not performed, despite an appropriate risk assessment having been carried out, but only movement restriction was implemented. The subjective parameter 'pain' requires assessment and interpretation by a specialist, as does the parameter 'obviously severely injured'.

Fig. 26.4 The immobilisation traffic light for adult, communicative patients. ABC problems in unstable patients take priority over immobilisation. For "yellow" patients or those with more than one point on the 45 scale, a clear justification should be provided if, after appropriate risk assessment, immobilisation is not performed and only movement restriction is applied. The subjective parameter "pain" requires assessment and interpretation by specialised staff as well as the parameter "obviously severely injured". *TBI* Traumatic brain injury; *GCS* Glasgow Coma Scale; *NRS* Numeric Rating Scale (Häske et al. 2022)

26.8 Abdominal Trauma

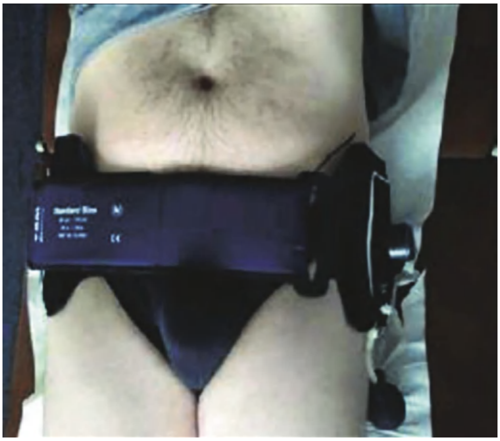
Abdominal trauma is among the less common injury patterns in alpine settings. Nevertheless, it is highly relevant, as intra-abdominal bleeding can be very difficult to control without invasive measures (Aufmkolk and Nast-Kolb 2001). In cases of massive abdominal haemorrhage, mortality within the first 20 min after trauma is up to 40% and within the first 50 min up to 50%. After this phase, mortality increases linearly by about 1% every 3 min. Missed abdominal injuries are among the most frequent preventable causes of death in multiple trauma.

Blunt abdominal trauma is about four times more common than penetrating or open injuries. In general, the mortality rate of blunt abdominal trauma is roughly twice as high as that of penetrating trauma. Combined injuries involving the head, thorax, pelvis, and extremities are common. In descending order of frequency, the spleen, kidneys, liver, gastrointestinal tract, bladder, and pancreas are affected. Injuries to abdominal organs are often invisible externally. The leading symptoms, as in acute abdomen, are tenderness and, if present, guarding. Attention should also be paid to bruising, provided that the external and situational circumstances allow such an examination. In acute management, the patient should be positioned and transported with the upper body slightly elevated (to relax the abdomen) and in the most comfortable position possible. As with all abdominal trauma, regular monitoring and (re-)assessment of the patient are essential.

26.9 Pelvic Trauma

Pelvic trauma is usually caused by direct force or rotational side impact. However, axial compression injuries may also result in severe pelvic injuries. Severe, unstable injuries are typically the result of high-energy trauma. In mountain environments, the vast majority of cases are due to falls from great heights or high-speed impact injuries.

Pelvic ring fractures as well as acetabular fractures are prominent in severe pelvic trauma. These injuries usually involve large bone fractures and wounds, which may lead to difficult-to-control bleeding. In cases of iliosacral disruption, blood loss from the presacral venous plexus of up to 4 l has been reported (Tullington et al. 2023; Lechner and Treffer 2017). Clinically detectable pelvic instability must be regarded as critical and acutely life-threatening and should therefore be referred for further diagnostics and treatment as quickly as possible. Typical symptoms include immobilising pain, compression pain over the pelvis, and possibly haemodynamic instability. In addition to analgesia and the gentlest possible positioning (ideally on a vacuum mattress), the acute management of a palpably unstable pelvic injury consists, if in doubt, of compressing the iliac crests towards each other. The pelvic sling should be applied at the level of the greater trochanters, just below the iliac crests (◘ Fig. 26.5). In addition, it is important to maintain body temperature and to regularly monitor and (re-)assess the patient.



◘ **Fig. 26.5** Applied pelvic sling. (Gather et al. 2017)

26.10 Trauma of the Upper Limb

26.10.1 Shoulder Dislocation

Anterior shoulder dislocation is the most common dislocation in humans, accounting for approximately 2–3% of all injuries and about 20% of all shoulder injuries in mountain trauma (◘ Fig. 26.6). In up to one third of cases, there is an associated rotator cuff injury.

The typical mechanism of injury is a fall onto the externally rotated, abducted arm. This protective movement of the arm is usu-

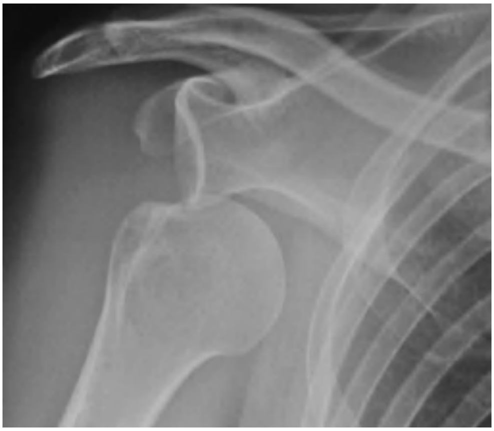


Fig. 26.6 X-ray of an anterior shoulder dislocation (© Simon Euler)

ally instinctive in humans to counteract the risk of head injury during a fall.

Clinically, an obvious palpable "dimple" is usually found beneath the now very prominent acromion. The arm is held painfully in a forced adducted position, with the forearm flexed at the elbow towards the body and supported by the uninjured hand. The leading symptom is pain. Initial assessment of peripheral circulation and sensation is of great importance, as the axillary nerve may be injured due to its proximity to the glenoid. If, for any reason, a reduction is performed and a neurological deficit is present afterwards, it is no longer possible to determine when the injury occurred. The sensory territory of the axillary nerve is the lateral shoulder region. Lesions of the brachial plexus are rare.

For indications for reduction, see ► Sect. 26.12.3. An efficient and gentle method of reduction is the Kocher or Milch technique (Ashton and Hassan 2006). Ideally, the patient is seated semi-upright, leaning against a stable back support or a backpack. The arm, flexed at the elbow, is slowly brought into abduction and external rotation simultaneously. With continuous traction, the dislocated head can also be palpated in the axilla and carefully manipulated forward and upwards (◘ Fig. 26.7).

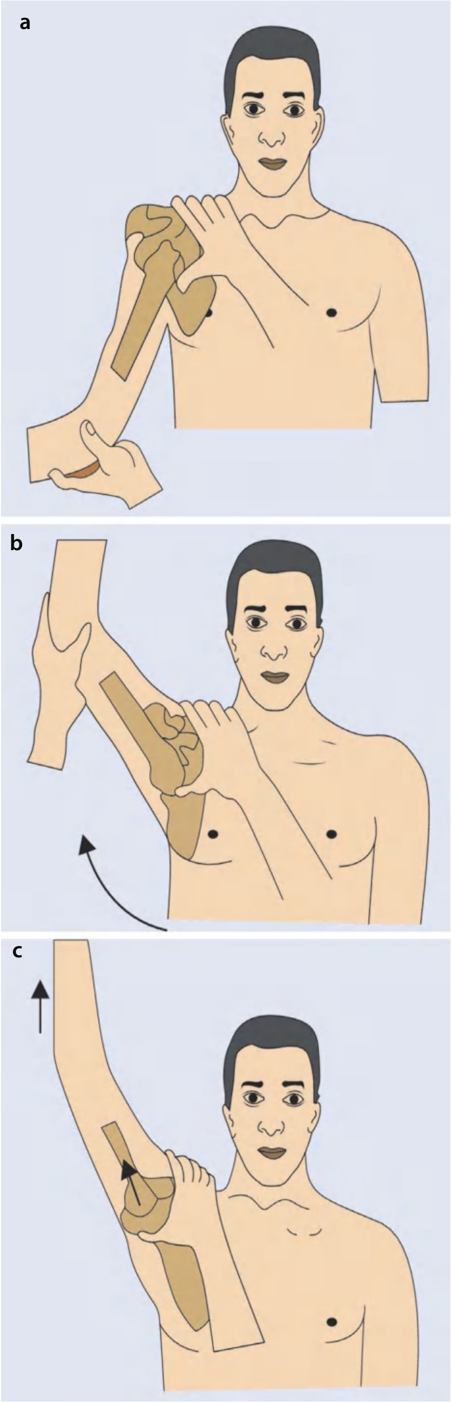


Fig. 26.7 Illustration of the steps of shoulder reduction according to Kocher/Milch. For details, see text. (VanBaak et al. 2020)

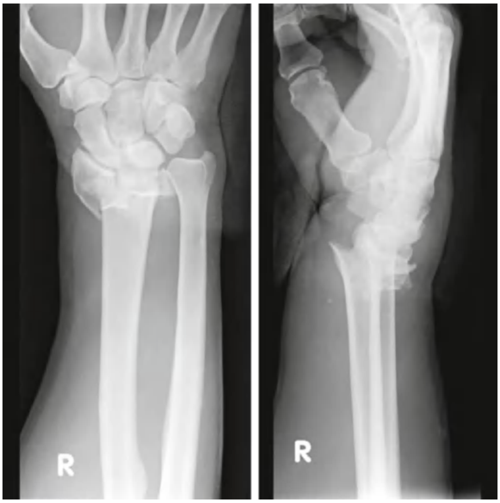
The advantage of this method is its gentle nature, transmitting little force compared to other techniques. This potentially minimises the risk of iatrogenic fracture.

26.10.2 Clavicle and Acromioclavicular Joint

Approximately 30% of all shoulder injuries involve the clavicle and the laterally adjacent acromioclavicular joint. The mechanism is typically a direct fall onto the shoulder with the arm at the side. The force is subsequently transmitted to the area of least resistance, either at the acromioclavicular joint or more medially in the clavicle. Clinically, such injuries are usually clearly recognisable. For immobilisation, a triangular sling or an improvised rescue blanket can be used to transfer the weight of the forearm to the cervical spine and keep the arm relatively still.

26.10.3 Distal Radius and Wrist

Of all major injuries in the mountains, fracture of the distal radius is the most common fracture (▣ Fig. 26.8). The injured person breaks their fall forwards on the extended wrist to protect the head from impact. In addition to initial assessment of peripheral circulation and sensation, malleable splints are suitable for provisional immobilisation; when well fitted and secured, these can also provide sufficient analgesia.



▣ **Fig. 26.8** X-rays of a distal, intra-articular, and grossly displaced radius fracture

26.11 Trauma of the Lower Limb

26.11.1 Hip and Thigh

Proximal femoral fractures are relatively rare injuries in mountain trauma.

The underlying cause is a lateral fall onto the greater trochanter. Fractures in the proximal hip region are typically extremely painful and immobilising injuries. In cases of significant displacement, muscle and tendon traction on the distal fragment may clinically result in a characteristic external rotation and shortening of the affected leg.

Fracture of the femur is a rare but potentially dangerous injury, particularly in mountainous environments. Blood loss from a femoral shaft fracture can reach up to 3 l.

In healthy individuals, a femoral shaft fracture requires a considerable force. As a result, such fractures often occur in combination with other injuries. Severe malalignment should be corrected to the anatomical axis as much as possible, if only to facilitate positioning and transport.

For positioning and evacuation, adequate analgesia and immobilisation on a vacuum mattress should be provided whenever possible. It is essential to ensure the patient is kept warm.

26.11.2 Knee

In downhill skiing, the knee is the most frequently injured body part—approximately 30–40% of all injuries. The firm attachment of leg to ski acts as a large lever arm and can result in extreme rotational and shearing forces on the knee joint. Intra-articular knee injuries are therefore typical injury patterns in this context. Rupture of the anterior cruciate ligament has led the statistics for years, accounting for up to 20% of all skiing injuries (Rauch 2022). The leading symptoms, in addition to potentially immobilising pain, include a sensation of instability.

For evacuation, immobilisation and usually supine positioning are necessary, as it is often difficult or impossible to clinically distinguish between intra-articular injuries and periarticular fractures during the initial assessment.

26.11.3 Lower Leg

Lower leg fractures account for approximately 7% of all skiing injuries and therefore play a significant role in mountain trauma. As with knee injuries, rotational and bending forces against the fixed foot (“vice effect”) may result in extreme forces on the tibia and fibula. In addition to severe pain, malalignment is often present and should be reduced on site whenever possible. This is particularly important in the presence of impaired peripheral circulation and/or sensation. For lower leg fractures, immobilisation in the supine position on a vacuum mattress is also recommended whenever possible.

26.11.4 Ankle Joint

Accounting for around 20% of all injuries in mountainous environments, the ankle joint is one of the most frequently injured body parts. Supination mechanisms are most common, with pronation injuries occurring less frequently, typically on uneven terrain. Clinically, it is difficult or impossible to distinguish between ligament injuries and fractures. The general rule is: when in doubt, avoid weight bearing and immobilise. A dislocated ankle joint should be reduced on site and stabilised in an appropriate splint, if possible. This is especially important in the presence of impaired peripheral circulation and/or sensation. For indications and procedures regarding reduction, see ► Sect. 26.12.3.

26.12 Practical Acute Care in Mountain Environments

26.12.1 Wounds and Wound Management: First Aid Kit

Penetrating skin injuries are among the most common types of trauma in mountain settings. In summer, when only light and short clothing is worn, lacerations, crush wounds, and abrasions of all kinds are most prevalent. In winter, sharp-edged sports equipment may cause deep, penetrating incision wounds. All of these wounds should be considered potentially contaminated and at risk of infection. Immediate management of any wound with disinfection and application of an appropriate (pressure) dressing is extremely important, as the time to professional care may be prolonged. In cases of heavy contamination, rinsing with water may be advisable.

Persistent bleeding from wounds may lead to significant blood loss over time and therefore pose an acute threat to life. The application of an appropriate compression dressing is therefore of great importance. In recent years, compact, highly effective, and easy-to-use dressing systems have become available, which can also be used effectively by amateurs. The use of a tourniquet for the management of severe extremity bleeding or amputations continues to be recommended (Wellme et al. 2021). However, this requires the tourniquet to be applied tightly enough to occlude blood flow, which is often difficult to achieve without adequate analgesia. Precise documentation of the time of application is essential. The maximum duration of tourniquet application should not exceed 100–120 min (Latina et al. 2021).

The general rule in mountain environments is: it seems to be beneficial to organise external professional assistance early rather than late. It is strongly recommended that every participant carry an appropriate first aid kit and is familiar with its use in case of emergency. A suggested content list for a compact first aid kit may be as follows:

Outer packaging should be as waterproof as possible.

- Analgesics (e.g. paracetamol tablets, ibuprofen tablets, if appropriate fentanyl lozenges)
- Wound dressings (plasters, 2 elastic bandages 8 cm, 1 to 2 sterile compresses 10 × 10 cm, Israeli/Compression bandage, Steri-Strips)
- Self-cooling elastic bandage (vacuum-packed)
- SAM splint
- Emergency blanket
- Two pairs of gloves in the appropriate size

Further details on emergency equipment for mountaineers and mountain doctors can be found in ▶ Chap. 40.

26.12.2 Fractures and Fracture Management

Many fractures of the upper limb can be provisionally stabilised on scene using simple means, allowing the injured person to independently reach urban areas or the nearest location for ground-based evacuation. Mouldable splints are particularly suitable for this purpose, as they can be used in combination with bandages to adequately immobilise the affected limb. Nevertheless, it is important not to underestimate the distance to be covered and the prevailing environmental conditions. In case of doubt, the professional rescue chain should be contacted as early as possible.

Fractures that prevent self-rescue should always be regarded as serious injuries and require prompt and gentle management. In the acute phase, provisional splinting and positioning in the most comfortable position possible are crucial. Sufficient warmth must be maintained (even in summer!). Fractures of the major long bones and the pelvis can potentially lead to significant blood loss (up to 4 l for the pelvis, up to 3 l for the femur, and up to 1 l for the lower leg and upper arm). This must be considered when planning the mode of evacuation and the time until definitive professional care becomes available.

Open fractures should be covered as quickly and as securely as possible with a sterile dressing. Primary photographic documentation can help ensure that the initial sterile dressing needs to be removed only in the treatment centre, or preferably in the operating theatre. This effectively reduces the risk of contamination.

In addition to the acute measures mentioned, it is essential for subsequent, sometimes critical, decisions that an accurate chronology of events and the timing of therapeutic interventions are documented and communicated.

26.12.3 Dislocations and Reductions

For those without experience, the reduction of a fractured bone or a dislocated joint in an emergency may present an extreme challenge for the person on site. Nevertheless, in cases of impaired peripheral circulation, motor function, and/or sensation, reduction may not only be potentially decisive for limb preservation but also crucial in preventing permanent sequelae. In addition, with few exceptions, it is the most effective form of pain management. Generally, a grossly misaligned fracture of a long bone is realigned by applying longitudinal traction and then immediately splinting the bone to prevent renewed malpositioning. This is particularly true for the lower leg, where the procedure is facilitated if muscle tension due to pain is adequately counteracted. It can be very helpful to flex the joint closest to the body. The same applies to dislocations or fracture-dislocations, especially at the upper ankle joint. If symptoms are tolerable and there is no impairment of sensation, motor function, or circulation, a dislocated joint does not necessarily need to be reduced on site. The hip joint should not be reduced outside a hospital setting, as (except in the case of a total hip replacement) reduction usually requires extensive muscle relaxation and at least procedural sedation.

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Multiple Trauma in the Mountain Environment

Guenther Sumann and Simon Rauch

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27.1 Definition of Terms

There is no single, clear definition of the term “multiple trauma”. A publication from 2009 described no fewer than 47 different definitions (Butcher and Balogh 2009). An Injury Severity Score (ISS) ≥16 is often used as the basis for defining severe trauma or multiple trauma. The ISS quantifies the severity of multiple injuries. It takes into account the most severe injuries in six body regions and is calculated as the sum of the squares of the highest Abbreviated Injury Scale (AIS) codes in the three most severely affected body regions (Gennarelli and Wodzin 2006; Baker et al. 1974). While the ISS describes an injury pattern, it does not assess the degree of threat to life. In the search for a more up-to-date definition, the “Berlin Definition” was developed by consensus of an international expert group. It considers significant injuries with AIS ≥3 in two or more different body regions and an ISS ≥16 in combination with one or more of five physiological parameters: arterial hypotension (systolic blood pressure, SBP ≤90 mmHg), impaired consciousness (Glasgow Coma Scale, GCS ≤8), acidosis (base excess ≤−6), coagulopathy (International Normalised Ratio, INR ≥1.4; partial thromboplastin time, PTT ≥40 s), and age ≥70 years (Pape et al. 2014). Among 11 multiple trauma definitions, the “Berlin Definition” was rated as the most suitable in terms of accounting for mortality risk (Frenzel et al. 2017), but it is not applicable in the pre-hospital setting.

In mountain rescue, rapid initial assessment of the injury pattern and a subjective estimation of the severity of the threat to life are crucial for pre-hospital multiple trauma care. For this reason, the four-decade-old definition by Tscherne appears to be the most practical: “The simultaneous injury of more than one body region, with at least one injury or the combination of injuries being life-threatening” (Tscherne et al. 1984).

27.2 Mechanisms of Injury in Mountain Accidents

Mountain sports are increasingly popular, with many activities in mountainous terrain practised by countless “mountain enthusiasts”, especially during the peak tourist seasons in summer and winter. These include mountaineering, hiking and trekking, trail running, mountain biking, downhill biking, downhill skiing, freeriding, cross-country skiing and ski touring, snowshoeing, tobogganing, paragliding, hang gliding, canyoning, kayaking, as well as extremely hazardous activities such as BASE jumping and wingsuit flying. A significant upward trend in serious injuries has been recorded in recent years in e-mountain biking. It seems that e-bikes are used by less fit or experienced individuals, often older people, in steep regions they would not be able to access with “bio-bikes” (bikes without electric motors). However, after the assisted ascent, they must tackle the demanding descent on steep and difficult trails with their heavy bikes, putting them at risk of falls and injuries (ÖKAS 2021). Many people live and work in the mountains. Injuries sustained during occupational accidents in mountainous terrain can be very severe, such as in forestry accidents, on mountain farms, during work for cable car companies, avalanche commissions, road construction, and so on.

Mountain accidents often involve injury mechanisms with high impact energy (high-speed or high-velocity trauma), which can result in multiple trauma. High speeds are typical in skiing, snowboarding, and mountain biking. Accordingly, injury patterns after skiing accidents can be severe (Corra et al. 2012; Furrer et al. 1995), especially after collisions with hard obstacles such as trees or rocks, or in collisions with other skiers. The use of ski helmets has reduced the rate of severe head injuries (Ackery et al. 2007), but skiing can still cause very serious traumatic brain injuries (TBI). Falls occur during climbing on exposed rock and ice, on steep snow, wet grass, or even on hiking trails. Other causes of falls include cornice collapse, avalanches, paragliding, and rock or icefall. The mountain sports activities most frequently leading to multiple trauma are skiing and snowboarding (approx. 30%), followed by hiking/trekking (approx. 20%) and mountaineering (approx. 15%) (Rauch et al. 2018).

In very remote mountain regions, the chances of survival after multiple trauma are predictably low. In contrast, in the European Alps, in areas with a very high density of air rescue bases, short arrival times, and short transport times to trauma centres, even cases of severe multiple trauma can be survived, sometimes with good outcomes and without significant long-term sequelae.

27.3 Approach to the Emergency Site, Initial Assessment, and Safety

The safety of the rescue teams and the casualty must take priority and remain the focus throughout a mountain rescue operation. As soon as the rescue teams approach the emergency site, attention must be focused on assessing “objective hazards” (rockfall, icefall, avalanches, risk of falling). When a helicopter crew locates a casualty from the air, the pilot conducts a “high recon”. By circling above the accident site, the entire crew can gain an initial impression of the situation, the condition of the casualty, and potential hazards and discuss the course of action. The rescue team should only be deployed to the casualty once the situation has been assessed as sufficiently safe. In specific situations, it may be necessary to evacuate the injured person from the accident site as quickly as possible, before any medical treatment and without adequate splinting or spinal stabilisation (Ellerton et al. 2009). This applies when there is a risk of icefall, rockfall, or avalanches, or when visibility is threatened by incoming fog. In such cases, rapid evacuation of the severely injured person, even with little or no initial medical care, can be lifesaving (▣ Fig. 27.1). Deteriorating visibility can interrupt a helicopter rescue operation for hours or even prevent it entirely.

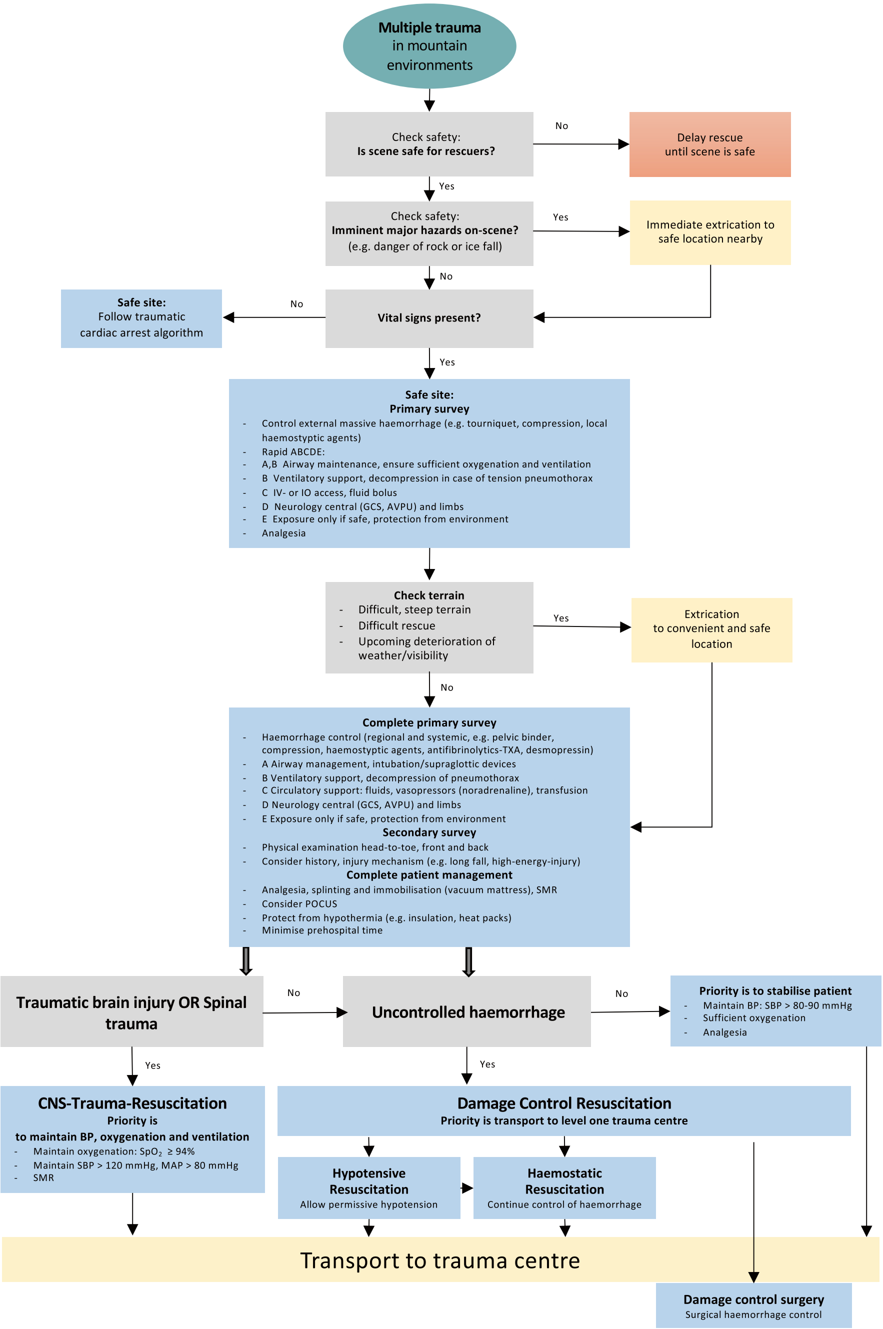

Multiple trauma in mountain environments
Check safety: Is scene safe for rescuers?
No
Delay rescue until scene is safe
Yes
Check safety: Imminent major hazards on-scene? (e.g. danger of rock or ice fall)
Yes
Immediate extrication to safe location nearby
No
Vital signs present?
No
Safe site: Follow traumatic cardiac arrest algorithm
Yes
Safe site: Primary survey
- Control external massive haemorrhage (e.g. tourniquet, compression, local haemostyptic agents)
- Rapid ABCDE:
- A,B Airway maintenance, ensure sufficient oxygenation and ventilation
- B Ventilatory support, decompression in case of tension pneumothorax
- C IV- or IO access, fluid bolus
- D Neurology central (GCS, AVPU) and limbs
- E Exposure only if safe, protection from environment
- Analgesia
Check terrain
- Difficult, steep terrain
- Difficult rescue
- Upcoming deterioration of weather/visibility
Yes
Extrication to convenient and safe location
No
Complete primary survey
- Haemorrhage control (regional and systemic, e.g. pelvic binder, compression, haemostyptic agents, antifibrinolytics-TXA, desmopressin)
- A Airway management, intubation/supraglottic devices
- B Ventilatory support, decompression of pneumothorax
- C Circulatory support: fluids, vasopressors (noradrenaline), transfusion
- D Neurology central (GCS, AVPU) and limbs
- E Exposure only if safe, protection from environment
Secondary survey
- Physical examination head-to-toe, front and back
- Consider history, injury mechanism (e.g. long fall, high-energy-injury)
Complete patient management
- Analgesia, splinting and immobilisation (vacuum mattress), SMR
- Consider POCUS
- Protect from hypothermia (e.g. insulation, heat packs)
- Minimise prehospital time
Traumatic brain injury OR Spinal trauma
No
Uncontrolled haemorrhage
No
Priority is to stabilise patient
- Maintain BP: SBP > 80-90 mmHg
- Sufficient oxygenation
- Analgesia
Yes
CNS-Trauma-Resuscitation
Priority is to maintain BP, oxygenation and ventilation
- Maintain oxygenation: SpO₂ ≥ 94%
- Maintain SBP > 120 mmHg, MAP > 80 mmHg
- SMR
Yes
Damage Control Resuscitation
Priority is transport to level one trauma centre
Hypotensive Resuscitation
Allow permissive hypotension
Haemostatic Resuscitation
Continue control of haemorrhage
Transport to trauma centre
Damage control surgery
Surgical haemorrhage control

Fig. 27.1 Algorithm for multiple trauma management in mountain terrain. *AVPU* Alert, Voice, Pain, Unresponsive; *BP* blood pressure; *cABCDE* Critical bleeding, airway, breathing, circulation, CNS assessment, hypothermia protection; *CNS* central nervous system; *GCS* Glasgow Coma Scale; *io* intraosseous; *iv* intravenous; *MAP* mean arterial pressure; *mmHg* millimetres of mercury, *POCUS* point-of-care ultrasound; *SBP* systolic blood pressure; *SMR* spinal movement restriction; SpO_2 peripheral oxygen saturation; *TXA* tranexamic acid. (Adapted from Sumann et al. 2020)

27.4 Initial Management, Primary Survey

The essential basis for the initial assessment of a casualty following a mountain accident is to obtain the most accurate information possible about the mechanism of injury. If high-velocity trauma is the cause, life-threatening injuries must be assumed, even if the patient reports little pain and there are no obvious external signs of injury. In the early phase after a dramatic accident, pain may be completely suppressed by high endorphin levels, which can mask severe injuries during the initial examination, as can the targeted administration of strong analgesics. In any case of high-energy trauma, even in the absence of visible signs of injury, it should always be assumed that the patient may have multiple injuries, until a comprehensive trauma assessment in hospital proves otherwise (Rieger et al. 2002).

The initial assessment of a severely injured patient in the mountains follows the Critical Bleeding or Exsanguination Approach (cABCDE or xABCDE; see overview) (Cornelius et al. 2023). In the mountain environment, particular emphasis should be placed on the E-Exposure point, in terms of the challenging environmental conditions.

Primary Survey of a Severely Injured Patient

- c Critical bleeding
- A Airway and cervical spine stabilisation
- B Breathing
- C Circulation
- D Neurological deficits
- E Hypothermia, environment, full-body examination

Life-threatening injuries, especially severe bleeding, should be identified rapidly. External bleeding must be managed without delay using direct compression, a tourniquet, or a haemostatic agent.

The airway and breathing should then be assessed. Acute respiratory failure in the pre-hospital setting is a particularly critical issue and, if at all possible, should be managed at the scene. The medical rescue team should clear and secure the patient's airway, administer oxygen, and decompress a possible tension pneumothorax. Induction of anaesthesia and endotracheal intubation, or alternatively the placement of a supraglottic airway device, may be necessary.

Initial circulatory stabilisation is also important. In cases of unwitnessed traumatic cardiac arrest, the chances of survival are generally low.

A brief neurological examination should be performed to assess the severity of central nervous system injuries. It is very important to record the level of consciousness at the scene using the GCS (Glasgow Coma Scale) or the AVPU scale (Alert, Verbal, Pain, Unresponsive), as well as limb movements, before the patient is anaesthetised.

Cervical spine stabilisation using a cervical collar should, if possible, be performed at the scene in cases of multiple trauma. Recent studies call this practice into question.

A casualty in the mountains is highly sensitive to cold, precipitation, and wind and should therefore be protected as effectively as possible to prevent a drop in core temperature.

27.5 Advanced Emergency Care, Secondary Survey

After initial management, a thorough head-to-toe examination should be performed. This can provide important information about the condition of the injured person and inform the further course of the rescue operation. In cold and windy conditions, the casualty should not be undressed during the examination. By palpating the torso and extremities through the clothing, painful body parts or deformities can be detected. In the case of penetrating injuries or open fractures, small openings can be cut in the clothing to inspect the skin, control bleeding, and cover wounds with sterile dressings. Sensation and circulation can also be checked through small openings in the clothing. Key interventions prior to evacuation include application of a pelvic binder in cases of haemodynamic instability and suspected pelvic trauma, reduction and splinting of major fractures, and spinal stabilisation.

The reliability of monitoring devices is often significantly limited in cold and wet conditions. Finger clip sensors for pulse oximetry often do not work, and ear clips are usually more practical. A new technology using ear sensors that can measure both temperature and oxygen saturation appears to be promising.

Blood pressure cuffs may yield inaccurate readings when applied over clothing. Sometimes, monitoring a casualty at the emergency site is limited to clinical assessment and the experience of the emergency medical personnel, observation of the general condition of the injured person, and the physician’s intuition. Based on knowledge of the overall injury pattern and the changes in vital functions, important decisions must be made regarding the necessary emergency medical therapy in conjunction with possible rescue procedures and appropriate transport destination. The use of portable ultrasound devices (POCUS, “point of care ultrasound”) can be helpful in assessing injury severity in pre-hospital emergency medicine (Kirkpatrick et al. 2004). However, examination conditions at mountain emergency sites can be very challenging (Snaith et al. 2011). The use of POCUS should be guided by a clear clinical question, result in a relevant therapeutic or decision-making consequence, and should not unduly delay on-site care time (Sumann et al. 2020).

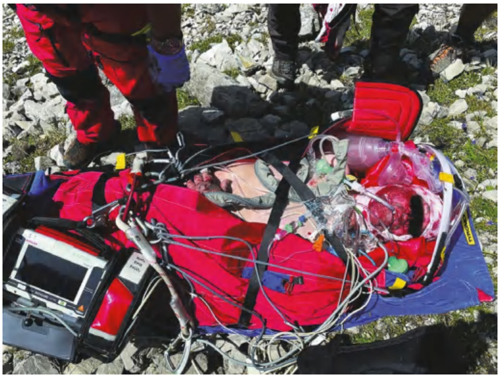
27.6 Strategy of Care and Rescue Procedure

The extent of emergency medical care in mountain accidents depends significantly on environmental factors, weather conditions, the steepness, exposure and remoteness of the incident site, the expected duration and type of rescue operation, and the time to hospital. Terrestrial mountain rescue operations can last many hours, are extremely demanding, and can significantly reduce the survival chances of a multiple traumatised casualty. The availability of an emergency medical helicopter (HEMS) is of critical importance. Using a rope rescue technique, the emergency team can be deployed directly to the casualty and, after receiving initial treatment, the injured person can be evacuated immediately in a rescue bag. This enables rescue operations to be carried out in a short time. Even if the emergency site is not directly accessible by helicopter due to weather-related limitations, a helicopter can still deliver rescue personnel and equipment close to the accident site, thereby significantly shortening the evacuation time. Alerting times can vary greatly in mountainous terrain (Tomazin et al. 2012). An observed accident in a region with excellent mobile network coverage in the Austrian Alps may allow for the arrival of HEMS within 15 min, possibly even enabling transfer to the emergency room within the “golden hour of trauma”. In contrast, an unobserved accident in a remote area, a search operation, or unfavourable flight conditions can result in rescue times of many hours. Generally, rescue times for multiple trauma incidents in the mountains are almost twice as long as in urban settings, particularly the “treatment-free” interval, i.e. the time from the accident to the arrival of rescue services (Rauch et al. 2018).

Cooling and hypothermia are dangerous complications for severely injured multiple trauma patients and increase mortality independently of injury severity (Azarkane et al. 2024). Time-consuming medical interventions at the scene should always be weighed against the risk of further cooling and prolonged shock. Emergency physicians require considerable experience and intuition to balance the appropriate level of treatment and on-site care time against the risk of dangerous delays during the rescue operation in the mountains.

Depending on the medical and mountaineering experience of the emergency physician, definitive emergency care including induction of anaesthesia, intubation, various invasive procedures, and adequate haemodynamic stabilisation can also be performed in exposed steep terrain. Transport of a ventilated patient in a rescue bag suspended from a helicopter line is safe and possible without problems (◘ Fig. 27.2).

However, in extreme terrain, a tiered approach to emergency care may sometimes be preferable. After brief initial management with analgesia, splinting, positioning, oxygen administration, and volume bolus, the injured person is evacuated to a flat and safe location, using a rescue bag and vacuum mattress, and if necessary, a climbing harness. There, emergency medical therapy can be completed under more favourable conditions before the patient is flown to hospital (Sumann et al. 2020). The selection of an appropriate primary receiving hospital, i.e. a trauma centre, and rapid transport thereto are crucial for the outcome of a severely injured patient (Zhu et al. 2018; Harrington et al. 2005).



◘ **Fig. 27.2** Multiple trauma following a 200-metre fall over steep, rocky terrain. Complete emergency medical care at the scene, followed by helicopter line rescue. (Image rights: G. Sumann)

27.7 Stabilisation of Vital Functions

27.7.1 Critical Bleeding (c)

Penetrating or open vascular injuries are rare in cases of multiple trauma following mountain accidents. Haemostasis in the event of massive external bleeding takes priority over all other components of the ABCDE algorithm (cABCDE) and can be achieved by compression, application of a tourniquet, and the use of locally acting haemostatic agents (for example, kaolin-impregnated haemostatic gauze or powders such as QuikClot®) (Schauer et al. 2017). In mountain rescue, the use of haemostatic gauze can be life-saving, as timely access to surgical intervention in hospital is often not possible. Tourniquets are the method of choice for exsanguinating limb haemorrhage and can be left in place for 2–6 h (Bulger et al. 2014; Chang et al. 2017; Kragh and Dubick 2017).

Blunt trauma mechanisms with inner organ injuries and internal bleeding are more common. In such cases, rapid transport to hospital is the top priority. Pelvic fractures are associated with increased mortality (Schulman et al. 2010). The lower pelvic region is rich in arterial collateral networks and an extensive venous plexus. Severe pelvic fractures carry a significant risk of massive haemorrhage into the pelvis. In unstable pelvic fractures, compression with a pelvic binder is important to reduce venous bleeding (Bakhshayesh et al. 2016; Höch et al. 2021).

Severe trauma is associated with major coagulopathies, resulting in trauma-induced coagulopathy (TIC). Coagulation competence is further impaired by hypothermia or haemodilution due to large infusion volumes (Simmons and Powell 2016). Pre-existing use of anticoagulants is particularly dangerous in severe trauma. All these factors can lead to severe, prolonged, life-threatening bleeding. Key objectives of pre-hospital therapy are to avoid dilutional coagulopathy and to protect against hypothermia (Hubetamann et al. 2011). Administration of 1 g tranexamic acid i.v. within the first 3 h after trauma is established practice in cases of severe bleeding, followed by 1 g over 8 h (CRASH-2 2010; Roissant et al. 2023). Early administration of fibrinogen concentrate is standard in-hospital care (Innerhofer et al. 2017) and is increasingly being used in pre-hospital emergency medicine (Ziegler et al. 2021). Other therapeutic approaches, such as desmopressin for cold-induced coagulopathy or prothrombin complex concentrate, are under discussion (Ng et al. 2011; Matsushima et al. 2015).

Pre-hospital blood transfusions should be considered as part of a damage control resuscitation strategy and reserved for high-risk patients in haemorrhagic shock. Whole blood would be the replacement fluid of choice in cases of major blood loss, but is only used in certain regions with very long transport times, primarily in military settings. The logistics of cooling and storing blood products are complex, and legal requirements for transfusions vary between countries. For this reason, packed red blood cells and freeze-dried, lyophilised plasma ("fresh frozen plasma", FFP) are only used to a limited extent in pre-hospital emergency medicine or mountain rescue (Eliassen et al. 2016; Bjerkvig et al. 2016).

Some air rescue organisations carry blood components (particularly packed red blood cells and plasma). However, the evidence regarding the benefit of pre-hospital administration of blood products is controversial (Sperry et al. 2018; Moore et al. 2018; Crombie et al. 2022). There is no clear recommendation for pre-hospital use of blood products (Rossaint et al. 2023).

27.7.2 Respiratory Failure (A, B)

Loss of consciousness following traumatic brain injury (TBI) or aspiration can lead to airway obstruction. In such cases, airway clearance, the recovery position, and administration of oxygen can be the decisive, life-saving initial treatment. Neurotrauma, such as TBI or high spinal cord injury, can cause central respiratory paralysis. Severe thoracic injuries, including multiple rib fractures, pulmonary contusions and lacerations, and tension pneumothorax, are causes of acute respiratory failure in severely injured patients. In all these cases, advanced airway management is indicated (Lockey et al. 2015).

The primary objective in the management of respiratory failure is airway protection and the support of adequate oxygenation and ventilation. In mountain rescue operations, challenging rescue procedures and potentially prolonged transport times must be considered when making decisions about airway management and ventilation therapy. During lengthy rescue missions, the benefit of a secured airway is significantly more important than during straightforward transport in urban settings, where the patient is always accessible for interventions if necessary. However, when ventilation is necessary during a prolonged terrestrial rescue, it is crucial that sufficient quantities of oxygen and anaesthetic agents are available for the entire duration of the rescue and evacuation of the casualty.

Endotracheal intubation with a correctly positioned and cuffed tube is the gold standard for airway management (Fevang et al. 2017; Pepe et al. 2015). It provides protection against aspiration, ensures optimal oxygenation and ventilation, and at the same time allows for deep anaesthesia to reduce stress and pain (Bein et al. 2013). However, pre-hospital induction of anaesthesia and endotracheal intubation are subject to controversy due to the reported possible high risk of tube misplacement (Haltmeier et al. 2017). Furthermore, following induction of anaesthesia and invasive ventilation, deterioration of haemodynamics should be anticipated. The success and safety of pre-hospital anaesthesia induction and intubation depend on the experience of the emergency medical team (Bossers et al. 2015; Timmermann et al. 2007). The use of videolaryngoscopes with bougie is recommended (Angerman et al. 2018). Rapid sequence induction (RSI) and emergency intubation are standardised procedures for experienced practitioners. However, for less experienced personnel, it appears to be safer and more efficient to use alternative airway management methods, such as a supraglottic device (e.g. laryngeal mask airway, laryngeal tube, Combitube). In physician-based emergency medical services in Europe, pre-hospital endotracheal intubation is common practice and is generally considered safe (Ausserer et al. 2017). To reduce the risk of unrecognised tube misplacement and to ensure correct ventilation settings, capnometric or capnographic monitoring must be used (Paal et al. 2010). In the event of intubation difficulties, it is important to ensure sufficient oxygenation by means of bag-mask ventilation or to use alternative airway management methods such as supraglottic airway devices. In a “can’t intubate, can’t oxygenate” (CICO) situation, a cricothyrotomy should be performed (Young 2003; Langeron et al. 2009).

A severely injured casualty in the mountains is subject to a massive adrenergic stress response due to pain, fear, hypovolaemia, and cold. The longer the wait for the arrival of the rescue team, the more the patient relies on this stress response to compensate for their circulatory status.

Induction of anaesthesia leads to the loss of most stress components, with the risk of severe circulatory failure up to cardiac arrest. Therefore, induction of anaesthesia in the multiple traumatised emergency patient is highly demanding, carries significant risk, and should only be performed by experienced personnel. The evacuation of an anaesthetised and ventilated casualty in a rescue bag during a helicopter line operation is a well-practised, standardised procedure, but nevertheless carries the risk of dangerous tube dislocation, which cannot be corrected while suspended on the line (Pietsch et al. 2018). In specific situations, as described above, a tiered approach is recommended, and induction of anaesthesia and ventilation should possibly only be performed after the line rescue operation.

Blunt thoracic trauma often occurs in mountain accidents, either as an isolated injury or as part of multiple trauma, particularly after falls, high-velocity trauma, or impact from ice or rock. The main symptoms are pain and respiratory distress. Adequate analgesia and administration of oxygen often result in a marked improvement in oxygenation, as the injured person is then able to breathe more deeply. Thoracic trauma contributes significantly to post-traumatic mortality, especially in combination with traumatic brain injury (Fokkema et al. 2023). Pulmonary injuries, haematopneumothorax and tension pneumothorax, severe injuries to the thoracic spine, and major internal haemorrhage due to vascular injuries including aortic and cardiac trauma can rapidly lead to massively life-threatening situations. Initially, significant thoracic trauma may sometimes go undetected. Lung ultrasonography is helpful in diagnosing pneumothorax, although it provides only limited assessment of its extent. Subcutaneous emphysema is an alarming sign, as it is diagnostic for a lung laceration with bronchopleural fistula. Key aspects of the acute management of thoracic trauma are respiratory function and the timely recognition of respiratory distress. Tension pneumothorax is the most common potentially preventable cause of death in multiple traumatised and multiply traumatised. In tension pneumothorax, life-threatening respiratory and circulatory failure leading to cardiac arrest can develop within a short period of time (Leigh-Smith and Harris 2005). The typical clinical picture includes signs of severe respiratory failure with circulatory shock and concurrent venous congestion (Roberts et al. 2015). If tension pneumothorax is suspected, immediate decompression of the pleural cavity must be performed. Needle decompression is the simplest and fastest initial emergency intervention, especially under challenging conditions during mountain rescue. The puncture is performed in the second to third intercostal space at the midclavicular line; more recently, the fourth to fifth intercostal space at the mid-axillary line has been recommended (Galvagno et al. 2019). Needle decompression must be followed by chest drain insertion, as otherwise a tension pneumothorax may recur. Chest drain insertion is not without risks (Chan et al. 1997). The "mini-thoracostomy" technique, in which blunt dissection is performed after a skin incision without a trocar, has the lowest complication rate (Hyde et al. 1997). Once the pleural cavity is opened, the lung surface is palpated with a finger. This allows the drain to be placed safely and correctly in the pleural space without a trocar. To save time, a defibrillator pad or transparent adhesive film can be used for temporary fixation of the chest drain. Respiratory insufficiency that persists despite oxygen administration and after exclusion of pneumothorax requires intubation and ventilation. It should be noted that with positive-pressure ventilation, there is a risk that a pneumothorax may rapidly enlarge. Liberal use of chest drains is controversial, and clinical data support a limited approach to chest drain insertion even in ventilated patients (Walker et al. 2018; Wilson et al. 2009). However, it is unclear whether limited indications for chest drain insertion are also appropriate during prolonged evacuation. An individualised approach, depending on the patient's clinical presentation and the planned rescue technique, is recommended. If immediate intervention is possible at any time during the rescue operation, a more conservative approach may be chosen. In case of doubt, especially before a prolonged extrication phase, a chest drain should be inserted. If, during ventilation, there is a sudden drop in oxygen saturation accompanied by significant arterial hypotension and tachycardia, a life-threatening tension pneumothorax should be suspected and immediate pleural decompression performed. During helicopter rescue operations in the mountains, it is important to note that rapid changes in flight altitude can significantly affect the expansion of a pneumothorax. During descent from the mountain to the valley, the increase in air pressure compresses a pneumothorax and naturally improves respiratory function. In contrast, ascent, for example, when flying over mountain ranges, can lead to a dangerous increase in the size of a pneumothorax and result in respiratory decompensation.

27.7.3 Circulatory Shock (C)

Severe haemorrhagic shock results in inadequate organ perfusion and oxygenation and is the second most common cause of death in multiple trauma, after traumatic brain injury (Valdez et al. 2016). Severe and persistent arterial hypotension is a typical problem in severe trauma and is often the result of internal bleeding due to organ or vascular injury, but may also be caused by generalised vasodilation due to systemic inflammatory response syndrome (SIRS) following extensive tissue trauma. In emergency situations in the mountains, especially when hypothermia is also present, it can be particularly challenging to recognise and accurately assess compensated circulatory shock. Arterial hypotension is often a late symptom of shock and may indicate a blood loss of >30%. Respiratory rate, heart rate, and level of consciousness are useful parameters that can be assessed even without monitoring equipment. Capillary refill time may be significantly prolonged and unreliable in low ambient temperatures and hypothermia (John et al. 2018). The absence or weakness of the radial pulse in combination with tachycardia is a good indicator of severe shock. Medications such as beta-blockers can slow the heart rate and mask the severity of circulatory shock. Multiple trauma patients taking oral anticoagulants are at particular risk of life-threatening haemorrhage.

Neurogenic shock occurs in spinal cord injury due to vasodilation of the lower body. In cases of high-level lesions, additional bradycardia may lead to severe circulatory collapse, which can only be managed with catecholamines. Another form of shock in severe trauma is obstructive shock caused by impaired cardiac filling in tension pneumothorax or cardiac tamponade. In these cases, immediate decompression by puncture of the pleural cavity or pericardium is required. In elderly patients with pre-existing cardiac disease, it should be considered that severe circulatory collapse following a mountain accident may also be the result of cardiogenic shock. In such cases, the cardiac event itself may have been the cause of the accident.

The aim of shock treatment is to improve tissue perfusion to maintain or restore organ function. In the pre-hospital phase, shock treatment should be guided by the concept of “damage control resuscitation”. Key objectives are haemorrhage control, securing oxygenation, prevention of hypothermia, avoidance of large-volume fluid replacement, and ensuring rapid transport to the nearest appropriate medical facility. Reversible causes of shock should be identified and treated promptly. External bleeding can be controlled by direct compression; in some cases, application of a haemostatic dressing (see ► Sect. 27.7.1) or a tourniquet proximal to the bleeding site is necessary. Reduction and stabilisation of major fractures, especially the use of a pelvic binder in unstable pelvic fractures, and rapid recognition and relief of tension pneumothorax are life-saving measures. To stabilise circulation, moderate amounts of fluids, preferably warmed, should be infused (Hahn 2013). Vasopressors may be required to maintain circulatory stability if the target blood pressure cannot be achieved with restrictive fluid therapy alone, or to counteract the vasodilatory effects of anaesthetics (Rossaint et al. 2023).

Permissive hypotension (“hypotensive resuscitation”) is a treatment strategy in which the systolic blood pressure (SBP) in blunt trauma is not raised above 80–90 mmHg in order to reduce bleeding and allow coagulation; in penetrating trauma, the target SBP is 70 mmHg (Rossaint et al. 2023). In prolonged rescue operations, this approach may sometimes be the only feasible treatment option (Sumann et al. 2009). However, it must be noted that mortality increases with the duration of hypotension (Chang et al. 2017). Prolonged periods with SBP <110 mmHg increase mortality in both penetrating and blunt injuries (Eastridge et al. 2007; Hasler et al. 2011). Permissive hypotension is contraindicated in patients with neurotrauma (see ► Sect. 27.7.4).

A traumatic cardiac arrest in mountain accidents is associated with very low survival rates, and prolonged resuscitation efforts are futile in most cases (Lugnet et al. 2023). Nevertheless, evacuation and transport with ongoing resuscitation may be indicated in certain exceptional cases, such as in severely hypothermic patients, when a witnessed cardiac arrest occurs, or when the transport route to a trauma centre is short. Performing chest compressions during rescue operations in steep terrain is difficult and probably impossible without interruptions. Therefore, mechanical resuscitation devices should be used (Thomassen et al. 2017; Pietsch et al. 2014). Despite the generally poor prognosis for patients with traumatic cardiac arrest, there are highly encouraging case reports of individual survivors of cardiac arrest after mountain accidents (Hill et al. 2013; Sumann et al. 2021).

27.7.4 Neurotrauma and Extremity Trauma (D)

The main therapeutic goals in neurotrauma (traumatic brain injury and spinal trauma) are the consistent stabilisation of oxygenation, ventilation, and blood pressure to prevent secondary injury and severe long-term sequelae. Even brief episodes of arterial hypotension and hypoxaemia are associated with increased mortality (Chesnut et al. 1993). A drop in systolic blood pressure below 120 mmHg alone significantly increases mortality in traumatic brain injury (Spaite et al. 2017). This makes the combination of neurotrauma with severe multiple trauma and haemorrhagic shock one of the most challenging scenarios in pre-hospital emergency medicine. Permissive hypotension is strictly contraindicated; instead, systolic blood pressure must be maintained consistently above 110 mmHg.

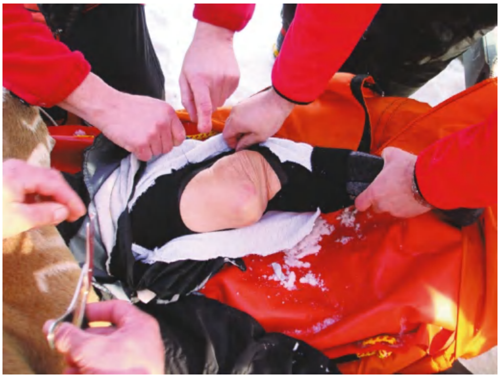
Unconscious patients (GCS ≤8) should be intubated to ensure adequate oxygenation and ventilation. Every pre-hospital intubation should be performed according to difficult airway protocols and, especially in traumatic brain injury, requires substantial experience in airway management and emergency intubation (Fakhry et al. 2006). If an unstable cervical spine fracture is suspected, manual in-line stabilisation must be maintained throughout the procedure (Boissy et al. 2011). Induction of anaesthesia and intubation under pre-hospital emergency conditions carry a high risk of arterial hypotension and deoxygenation. Prior to induction, a fluid bolus, circulatory stabilisation with vasopressors if necessary, and adequate preoxygenation are essential. In specific cases, it may be appropriate to postpone intubation until after technical rescue has been completed. End-tidal carbon dioxide values ($etCO_2$) should be set at 30–35 mmHg in patients without signs of cerebral herniation (Caulfield et al. 2009). In neurotrauma, rapid transport to a trauma centre with neurosurgical capability should be prioritised. In traumatic brain injury, helicopter transport is associated with higher survival rates (Bekelis et al. 2015). During transport, the patient should be positioned with the upper body elevated by approximately 30° to reduce intracranial pressure.

Complete immobilisation of the spine can be achieved by positioning the patient on a vacuum mattress with a cervical collar applied. When applying a cervical collar, correct positioning is essential to prevent obstruction of jugular venous outflow and the resulting increase in intracranial pressure (Karason et al. 2014). If horizontal positioning is not possible, for example, in narrow glacier crevasses, a Kendrick Extrication Device (KED) or similar can be used for crevasse rescue to stabilise the spine in a seated position (Winterberger et al. 2008).

In multiple trauma, significant extremity injuries occur in more than half of cases (Banerjee et al. 2013). In fractures of major long bones with gross displacement, realignment to the anatomical axis should be performed during initial management. Peripheral pulses and sensation should be assessed and documented before and after realignment. All fractures should be inspected to exclude external bleeding. If bleeding is detected, a thorough examination should follow. Bleeding should be controlled by direct pressure or, in the case of severe haemorrhage, by proximal tourniquet application. Open wounds should ideally be covered with sterile dressings. A transparent adhesive dressing such as OpSite® has the advantage that the skin over an open fracture can be inspected multiple times during handover without removing the dressing. All possible measures should be taken to control external bleeding. In cases of open fractures or large wounds, intravenous antibiotics should be administered if available, especially during prolonged rescue operations.

The pre-hospital management and positioning of multiple extremity injuries in critically ill multiple trauma patients should be pragmatic. It is often not possible to optimally immobilise every single fracture. Fractures of the lower extremities can be optimally positioned and immobilised in a vacuum mattress. For fractures of the upper extremities, additional splinting material is usually necessary, and flexible, rollable splints such as the SAM Splint® have proven highly effective for this. Severely injured patients should always be placed in large, full-body vacuum mattresses for transport. A vacuum mattress provides optimal stabilisation, protection, and pain relief, even during potentially rough transport, particularly in terrestrial mountain rescue scenarios.

Reduction of a joint dislocation is not a priority in the pre-hospital management of multiple trauma patients, unless the dislocation impairs patient cooperation due to pain or complicates transport. In terrestrial rescue of a casualty with an unreduced dislocated hip or shoulder, the joint should be stabilised and the limb splinted in the most comfortable position. The reduction of a traumatic anterior shoulder dislocation at the scene is controversial. In some countries, reduction is not recommended in cases of uncertain diagnosis without radiological confirmation, except in the presence of loss of peripheral pulses, sensory deficits, habitual dislocation, or significant positioning problems during evacuation (Foerster and Zafren 1998) (◘ Fig. 27.3).



◘ **Fig. 27.3** Locked knee dislocation following a skiing accident. Assessment after local exposure of clothing. (Image rights: G. Sumann)

27.7.5 Hypothermia in Multiple Trauma (E)

The combination of hypothermia, acidosis, and coagulopathy ("trauma triad of death") can dramatically reduce the survival chances of multiple trauma patients. Accidental hypothermia plays a crucial role in this context (Mikhail 1999; Tsuei and Kearney 2004). Hypothermia leads to severe coagulopathy. Therefore, adequate circulatory stabilisation and protection against further heat loss are vital in the management of multiple trauma. Cold infusions and undressing of the casualty should be avoided. Measures to prevent further heat loss include protection from weather and wind, minimisation of exposure time during examination and treatment, and use of insulating blankets and heat packs applied to the torso. For patients with wet clothing, wrapping the patient in vapour-impermeable layers creates a moisture barrier and thus a warming effect (Henriksson et al. 2015). This method is particularly effective when thick insulating blankets are used within the vapour barrier (Allen et al. 2010). If possible, all infusions should be warmed to 40 °C. A rescue bag protects the casualty from adverse weather conditions; in addition, a warm hat and protective goggles should be used in windy and cold conditions.

The most reliable method for measuring core temperature is an oesophageal temperature probe. However, correct placement of an oesophageal probe is only feasible in ventilated patients. Epitympanic measurement devices are easy to use and thus are frequently used but may yield false low readings if snow is present in the external auditory canal (Strapazzon et al. 2014).

27.7.6 Analgesia

Severely injured patients must receive adequate analgesic therapy. Sufficient analgesia reduces the subjective and physiological stress burden on the casualty and enables repositioning or evacuation. Analgesia is usually one of the first therapeutic steps before evacuating a casualty from the scene. Stable positioning and splinting, especially of extremity fractures, are an important foundation of analgesic therapy. For systemic pharmacological analgesia in multiple trauma, potent opioids or ketamine are usually used. In some cases, particularly during prolonged terrestrial rescue operations, regional anaesthesia techniques, such as peripheral plexus or nerve blocks, may be used.

Details of analgesic therapy are discussed in ▶ Chap. 35.

27.7.7 Positioning and Evacuation

The optimal positioning of the patient before and during evacuation depends on the type of injuries and the level of consciousness. In cases of reduced consciousness without a secured airway, the lateral position should be used (Hyldmo et al. 2015). A conscious patient can indicate the position in which they feel most comfortable, especially during prolonged rescue and transport. In thoracic trauma, elevating the upper body can facilitate easier breathing. In multiple trauma patients, the supine position generally provides the best combination of spinal stabilisation and, at the same time, optimal access to the casualty for diagnosis, monitoring, and interventions. If possible, patients with traumatic brain injury should be positioned with the upper body and head elevated at 30° to minimise the increase in intracranial pressure. The slope of the terrain can often be used to optimise positioning. Awake patients should generally be transported feet first. The use of a full-body vacuum mattress provides the best stability for positioning.

An important principle when repositioning the severely injured patient is to move them as little as possible and instead to slide the equipment underneath them. The "bridge carry technique" is a well-proven method. Three to four rescuers lift the casualty simultaneously and in a coordinated manner, while the vacuum mattress and rescue bag, with or without a stretcher, are slid underneath the patient, who is then lowered onto the vacuum mattress. If only a stretcher without a vacuum mattress is available, it should be equipped with padding and insulation to prevent pressure sores and heat loss.

During terrestrial evacuation, changes in body position and unpleasant or painful jolts are difficult to avoid. Therefore, the casualty should receive adequate analgesia. Helicopter line rescues are significantly gentler; however, it is practically impossible to perform interventions on the patient during line operations. In principle, necessary medical measures should be carried out before or after the technical rescue. In prolonged terrestrial rescues, breaks for interventions can be taken depending on the terrain.

During helicopter transport, the continuation of emergency treatment is possible to a certain extent, depending on the aircraft. However, many helicopters used in mountain rescue offer only limited space for invasive procedures. The casualty should be as well prepared as possible before take-off to minimise the risk of complications during transport. All necessary lines, tubes, and medical devices should be arranged for easy access. If complications are anticipated, the pilot should be prepared for a short-term landing so that further intensive care measures can be performed on the ground. A multiple trauma patient should be transferred to a high-level trauma centre as quickly as possible. A helicopter can cover long distances in a reasonable time to help achieve the best possible outcome for the patient (Zhu et al. 2018).

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Lightning Accidents in Mountainous Terrain

Peter Paal and Mathias Ströhle

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28.1 Prevention

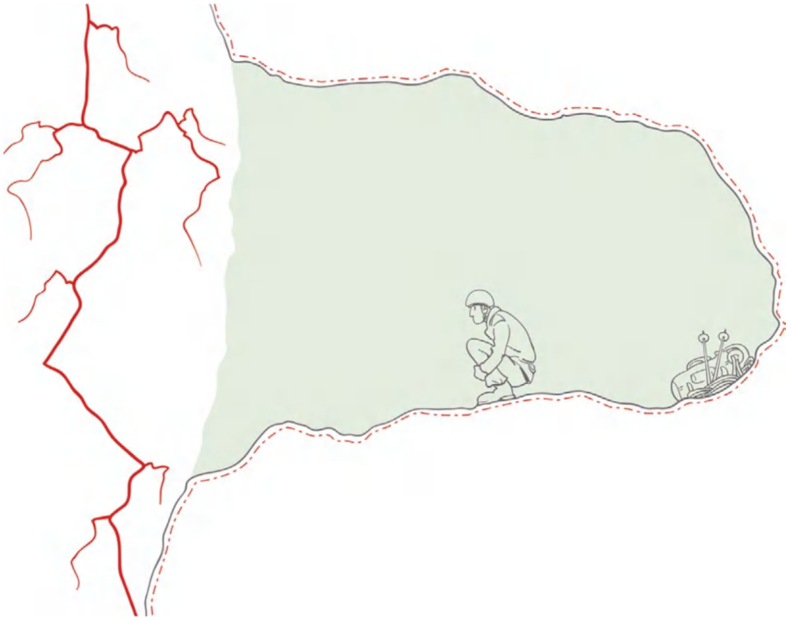
Avoiding outdoor exposure during a thunderstorm is by far the most important precaution. When planning mountain excursions, the current weather forecast should always be checked. Severe thunderstorms with lightning mainly occur in the summer months from June to August, between 12:00 and 18:00, when the atmosphere is most highly charged on hot, humid days.

Lightning usually forms near cumulus clouds, but can also strike several kilometres ahead of or behind a thunderstorm front. Thus, lightning can often occur unexpectedly, even under clear skies and without rain. One third of lightning strikes occur respectively before, during, and after the thunderstorm rain. The 30–30 rule states that the risk of being struck by lightning is high if the interval between lightning and thunder is less than 30 s (corresponding to a distance of 10 km), and that one should not go outdoors until 30 min after the last observed lightning strike.

The safest place during a thunderstorm is a hut or shelter with closed doors and windows. In small open huts and shelters, there is a risk of side flashes. Tents are also unsafe, as metal tent poles act as lightning conductors. Larger rock caves and hollows can provide safety, whereas small niches, overhangs, and water-filled stream beds may be even more dangerous than open terrain (◘ Figs. 28.1 and 28.2).

If caught in a thunderstorm in the mountains, keep away from ridges and summits, and avoid isolated trees, cable cars, ski lifts, and power lines. Near a rock face, there is a relatively safe triangle on the ground, the length of whose sides corresponds to the height of the wall. To reduce the risk of ground currents, it is advisable to keep a distance of at least 1 m from the wall (◘ Figs. 28.3 and 28.4).

A sparse forest offers more protection than an open clearing, where a person can act as a lightning rod. On a glacier, it is better to dig a snow cave and stay inside it, rather than remain exposed on the surface.



◘ **Fig. 28.1** Large rock caves provide sufficient protection against lightning strikes. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

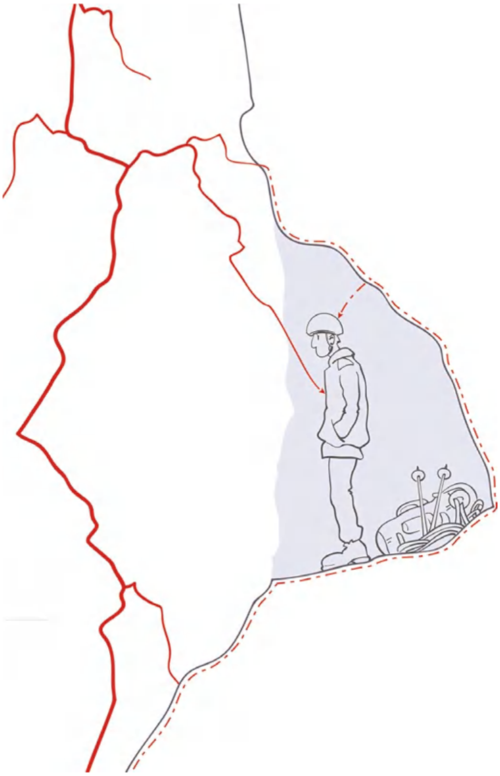


Fig. 28.2 Small rock caves do not provide adequate protection against lightning strikes. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

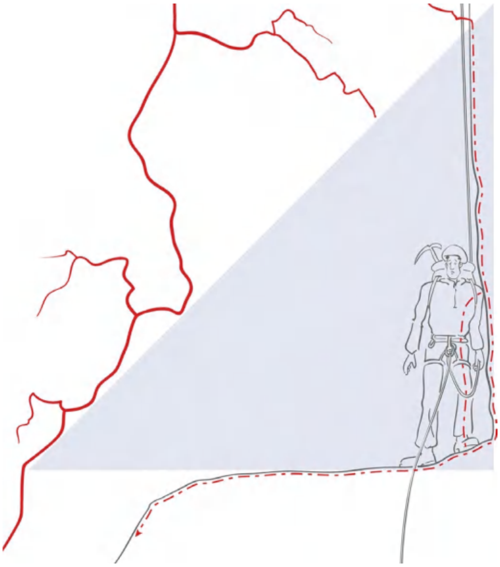


Fig. 28.3 Near a rock face, there is a relatively safe triangle on the ground, the length of whose sides corresponds to the height of the wall. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

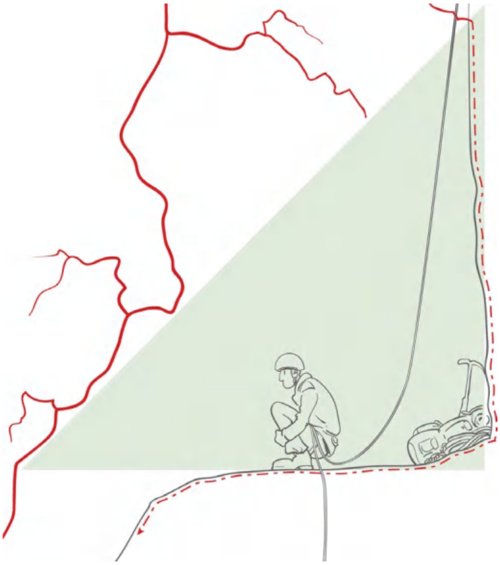


Fig. 28.4 Even within this relatively safe triangle, adopt the crouched position. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

In open terrain, crouch with feet together and touch the ground with the smallest possible surface area to avoid step voltage (◘ Figs. 28.5 and 28.6).

Sitting on a dry rope is an option, but do not lie flat on the ground. Contrary to popular belief, metal does not attract electricity, but it is a good conductor. Metal objects should therefore not be carried above shoulder height so as to minimise the risk of acting as a lightning rod (e.g. protruding ice axes, skis, or ski poles).

Electronic devices such as mobile phones or radios should be stored centrally in the rucksack. Ice axes, carabiners, climbing anchors, ski poles, and crampons should be

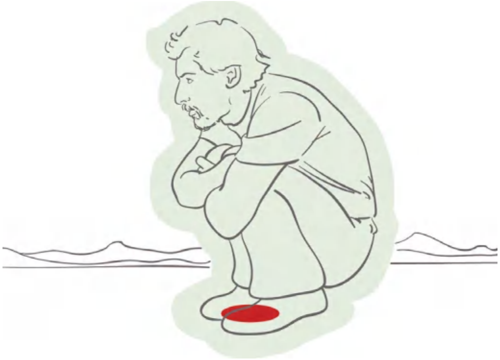


Fig. 28.5 In open terrain, crouch with feet together and touch the ground with the smallest possible surface area. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

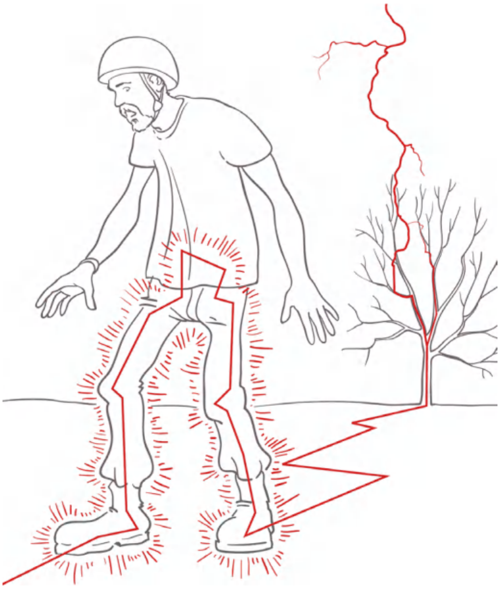


Fig. 28.6 If a person's legs are at different distances from the site of a lightning strike, a voltage gradient is created, allowing current to flow through the body. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

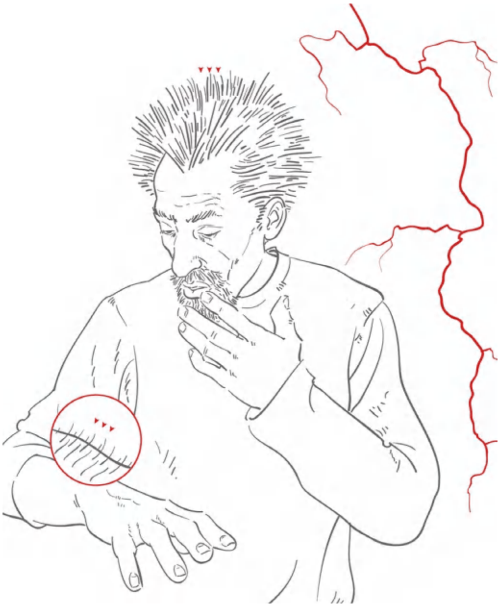


Fig. 28.7 If hair stands on end immediately crouch down with feet together. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

placed at a safe distance from the mountaineers. If metal objects are in direct contact with the skin, severe burns may occur in the event of a lightning discharge.

When climbing, continue to wear a helmet during a thunderstorm and remain secured to the wall to prevent head injuries from falls. On a via ferrata, move away from wire ropes and iron ladders if it is safe to do so. However, lightning can also follow wet climbing ropes. If a tingling sensation is felt on skin or hair stands on end (Fig. 28.7), then immediately crouch down with feet together.

Crackling or visible sparking at exposed sites—the so-called St. Elmo's fire—indicates an imminent lightning strike. If several people are exposed to a thunderstorm, they should keep a safe distance from each other to prevent a mass casualty incident in the event of a lightning strike.

Organisers of public events in mountainous areas should coordinate safety measures with the authorities, develop evacuation plans, and cancel or postpone the event in the case of an impending thunderstorm according to the 30–30 rule. Spectator stands should be protected with lightning conductors. The so-called lightning detec-

Table 28.1 Differences between lightning and high-voltage electrical injuries (Modified after Cooper et al. 2012)

Factor	Lightning injury	High-voltage electrical injury
Voltage/current	10–100 million volts, 50,000 amperes	Usually significantly lower
Duration of exposure	Few milliseconds	Seconds
Pathway	Over the body surface and through body orifices	Into the body interior
Burns	Superficial, minor	Deep, severe
Kidney	Minor myoglobinuria and haemoglobinuria	High risk of renal failure due to pronounced myoglobinuria
Fasciotomy	Rarely required	Often necessary early and extensively
Blunt injury	Explosive effect	Fall

tors, primarily used in North America for early warning, should also be considered for use elsewhere.

28.2 Mechanisms of Injury

In a lightning accident, usually only one person is affected. In contrast to electrical accidents involving relatively prolonged exposure, such as contact with power lines, lightning strikes result in massive current exposure of extremely short duration (Cooper et al. 2012). The differences between lightning strikes and electrical accidents are summarised in ◘ Table 28.1.

Various mechanisms of injury are possible:

- Individuals may be struck directly by the main lightning channel. Such incidents are usually fatal.
- More commonly, a so-called side flash jumps from a nearby tree or another object, such as a rock, to a person.
- Contact injuries can occur through touching objects that have been struck by lightning or conduct the lightning current, such as anchors, ropes, or ladders on a via ferrata.
- When lightning strikes the ground, the current spreads out radially. If a person's points of contact with the ground are at different distances from the strike site, a voltage gradient is created, allowing current to flow through the body between the two points of contact. This is referred to as step voltage (see ◘ Fig. 28.6).
- Injuries may also result from the shock wave of the lightning strike or from uncontrolled muscle contractions caused by the electric shock. For example, mountaineers may lose their balance and fall or be thrown from the rock face while climbing.

28.3 Injuries

Direct lightning injuries are caused by high voltage, heat generation, and explosive force. The most common causes of death are cardiac or respiratory arrest. Direct lightning exposure can induce ventricular fibrillation or asystole in the myocardium. Alternatively, lightning can cause primary respiratory arrest by paralysing the central respiratory centre in the brain, which then after several

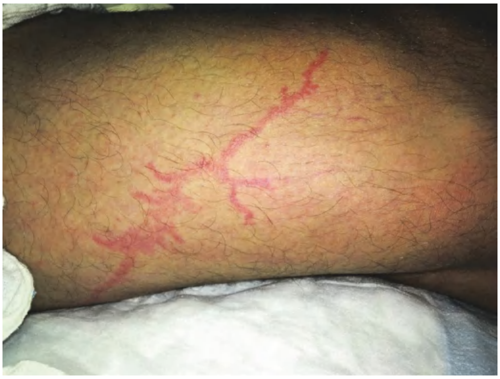


Fig. 28.8 "Lightning figures", Lichtenberg formation, on the body of a patient following a lightning strike. (With kind permission of Mathias Ströhle)

minutes leads to secondary cardiac arrest due to the associated hypoxia.

In this latter scenario, timely artificial ventilation can bridge the period until spontaneous breathing resumes. If cardiac activity does not return after 20–30 min of high-quality CPR, discontinuation of resuscitation may be considered (Lugnet et al. 2023). Indirectly, lightning strikes can also cause severe accidents due to falls.

Centrally mediated neuropsychiatric changes such as confusion, memory impairment, epileptic seizures, deafness, and blindness may also occur, but are usually temporary. Peripheral paralysis of the arms and legs caused by lightning strikes generally resolves within hours, but in rare cases may persist for months or even be permanent.

Burns are caused directly by the lightning strike and may appear on the skin as localised or linear lesions. Tree-like branching patterns on the skin, the so-called lightning figures, are not true burns but superficial efflorescences produced by an "electron shower". They are considered evidence of a lightning injury and often fade within hours (Fig. 28.8).

Burns frequently follow the body's sweat folds, such as the dividing line of the chest and abdomen or the mid-axillary line. The explosive evaporation of sweat can cause clothing and shoes to be torn from the body.

Table 28.2 Differences between acute and delayed lightning injuries (Modified after Cooper et al. 2012)

Acute lightning injuries	Delayed lightning injuries
Cardiac arrest and other myocardial injuries	Neurological impairments
Pulmonary injuries	Psychiatric abnormalities
Neurological impairments	Memory impairment
Epilepsy	Attention disorders
Hearing loss (e.g. due to tympanic membrane injury)	Personality changes
Amnesia and confusion	Emotional irritability
Vertigo	Chronic pain
Contusions from falls due to explosive force	Epilepsy
Muscle or skeletal injuries due to massive muscle contraction	

Lightning injuries may occur immediately or be delayed (Table 28.2).

28.4 Risk Assessment and Management During Rescue Operations

Rescue operations in thunderstorm conditions are highly hazardous. Thunderstorms endanger the safety of aircraft due to lightning, hail, and strong winds. In addition, the crew may be struck by lightning while providing initial care to the patient outside the helicopter. If there is a risk of lightning, rescue personnel must therefore balance the benefit of rapid evacuation for the patient against the risk to the rescue team and decide whether evacuation is justifiable.

28.5 Patient Assessment and Initial Management

As with all life-threatening emergencies, the first responder should check consciousness and breathing. If necessary, they should immediately initiate basic life-saving measures (Basic Life Support, BLS) and continue these until the emergency medical team arrives (Bray et al. 2025). BLS also includes the use of a semi-automatic external defibrillator (AED), which should be made available as quickly as possible in cases of lightning accidents (Elsensohn et al. 2011) in order to attempt conversion of ventricular fibrillation back to a normal cardiac rhythm (Greif et al. 2025).

Following a lightning strike, the paradoxical situation may arise in which the casualty has a detectable pulse but is not breathing (lightning-induced primary respiratory arrest). In this particular case, artificial ventilation alone is sufficient and should be continued until adequate spontaneous breathing resumes (Paal et al. 2006, 2007).

In cases of suspected severe injury, the casualty should be managed in accordance with current trauma guidelines (DGU 2022). However, the absence of external injuries does not rule out internal organ damage (▶ Chap. 26) and as sequelae of lightning injuries may only become apparent after several hours, lightning victims should, as a rule, be admitted to hospital for observation (Zafren et al. 2005). Any person presenting with linear burn patterns, neurological alterations, hearing loss, or clothing destroyed in an explosive manner should be treated as a lightning casualty.

> However, ultimately the safety of rescue teams takes priority.

28.6 Triage

In rare cases, a single lightning strike may affect several people simultaneously. In contrast to other triage situations, where casualties with preserved vital functions (consciousness, breathing, circulation) are treated first, in lightning accidents, cardiopulmonary resuscitation of those without vital signs takes precedence.

> Lightning victims benefit greatly from cardiopulmonary resuscitation if they have not sustained severe organ damage, as respiratory and cardiac arrest are reversible within the first few minutes if treated promptly. In cases of primary respiratory arrest, artificial ventilation alone may be life-saving.

Lightning myths that have been proven false include:

- It is dangerous to touch a lightning strike victim.
- Lightning never strikes the same place twice.
- Lightning always strikes the highest object.

> **Conclusion**
>
> During thunderstorms, ridges, summits, and isolated trees should be avoided. A distance of at least 1 metre from the rock face should be maintained to prevent surface currents. Lightning follows watercourses, wet ropes, wire cables, and metal ladders, and therefore these should be avoided. Crackling sounds, St. Elmo's fire, and hair standing on end indicate an imminent lightning strike; and a crouched position with feet together should be adopted. Initial management of lightning victims should always follow current resuscitation guidelines. Early defibrillation in cases of ventricular fibrillation or prolonged ventilation in isolated respiratory arrest can be life-saving.

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29

Accidental Hypothermia

Simon Rauch, Peter Paal, and Hermann Brugger

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29.1 Clinical Staging

29.1.1 The Original Swiss Classification

In the classic Swiss classification, accidental hypothermia is divided into four stages based on core temperature (CT) and clinical signs (i.e. shivering, level of consciousness, vital signs) (◘ Table 29.1) (Durrer et al. 2001, 2003). Shivering is the main symptom in mild and moderate hypothermia and usually ceases at a CT of <30–32 °C. The level of consciousness and onset of cardiac arrest are not always purely temperature-dependent, which highlights that the clinical signs of hypothermia can vary individually and may be influenced by comorbidities (e.g. intoxication) and the presence of trauma.

The original clinical staging system (Durrer et al. 2003) and the management of hypothermia are presented in ◘ Table 29.1.

- **Stage I**

Mild hypothermia: The patient is conscious, usually shivering, and may be agitated or confused; CT is generally between 35 and 32 °C. Heart rate and respiratory rate are increased due to elevated oxygen demand. In cases of very rapid cooling (e.g. in cold water), shivering may be suppressed even at this stage.

- **Stage II**

Moderate hypothermia: Consciousness is impaired, but the patient can be roused. Shivering is usually absent, breathing is shallow, and core temperature is between 32 and 28 °C. Although arrhythmias of any type may occur, the risk of cardiac arrest is

◘ **Table 29.1** Clinical original staging and management of accidental hypothermia

Stage	Clinical features	Core temperature[a] (in °C)	Management
I	Alert, shivering	~35 to ~32	Warm environment, warm sweet drinks, active movement if possible
II	Drowsy, no shivering	~32 to ~28	Monitoring Avoid movement Horizontal positioning Protection from cold Active external rewarming (warm environment, heat packs, warm infusions, forced-air warming blankets)
III	Unconscious, breathing present	~28 to ~24	In addition to stage II: Airway management With unstable circulation, rewarming using extracorporeal circulation
IV	No respiration, in some cases minimal vital signs	<~24	In addition to stage III: Cardiopulmonary resuscitation Maximum of three defibrillations Extracorporeal rewarming or, if not available, combined external and internal rewarming during cardiopulmonary resuscitation

[a] The core temperatures assigned to the stages are for guidance only and should be verified by measurement of core temperature

generally low. In individual cases, however—especially after rapid cooling (water, crevasse, avalanche) and with rapid movement—cardiac arrest (the so-called rescue collapse) may occur. With slow cooling, this risk is rather low (◘ Fig. 29.1).

▪ Stage III

Severe hypothermia with vital signs: The patient is usually unresponsive, but spontaneous breathing is present; core temperature is between 28 and 24 °C. Occasionally, patients with a core temperature below 28 °C may still be responsive. Pupils may be anisocoric, the light reflex is sluggish, and heart and respiratory rates are slowed. In the absence of obvious signs of life, breathing and the carotid pulse should be assessed for up to 1 minute. There is a high risk of cardiac arrest, especially with improper handling during rescue and after rapid cooling. In some cases, vital signs have been observed in patients with a CT below 24 °C.

▪ Stage IV

Severe hypothermia without vital signs: No vital signs can be detected, the body is cold and lifeless, and the condition closely resembles that of a dead, cooled patient ("apparent death"). However, due to the greatly reduced oxygen demand, survival without brain damage is possible even after prolonged cardiac arrest, provided the correct management decisions are made (Forti et al. 2019). If there are no unequivocally fatal injuries and the body is not frozen stiff, resuscitation must always be initiated. The decision to terminate resuscitation is a medical one.

◘ **Fig. 29.1** Evacuation of two hypothermic patients after two nights at 4000 m altitude. (Image rights: B. Durrer)

▪ Stage V

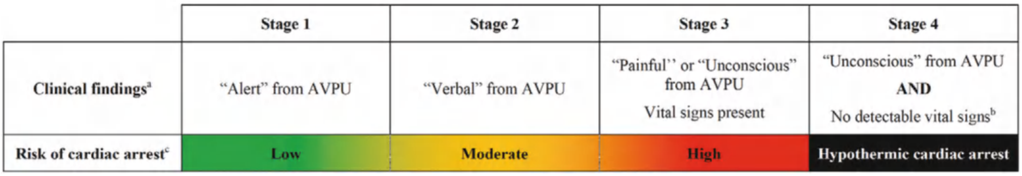
Irreversible hypothermic death: The most severe documented, yet reversible, case of accidental hypothermia had a CT of 11.8 °C; after therapeutic hypothermia, a patient survived at 4.2 °C (Zafren et al. 2020). As a rule, death from hypothermia should only be confirmed after a rewarming attempt, following the principle: "Nobody is dead until warm and dead".

29.1.2 The Revised Swiss Staging System

The revised Swiss staging system is based solely on assessment of the level of consciousness and should be used when measurement of CT is not possible and a central disorder, such as intoxication or traumatic brain injury, can be excluded (◘ Table 29.2) (Musi et al. 2021).

> Shivering should no longer be used for staging accidental hypothermia, as inter-individual differences are too great and shivering may be suppressed by concomitant factors such as traumatic brain injury or intoxication. Of all bodily functions, level of consciousness correlates most closely with CT and the risk of hypothermia-induced cardiac arrest (Pasquier et al. 2021). Therefore, in the absence of a reliable temperature measurement and after excluding confounding factors (such as CNS-impairing intoxication and traumatic brain injury), the level of consciousness is decisive for the clinical assessment

Table 29.2 Revised Swiss staging system (according to Musi et al. 2021)



	Stage 1	Stage 2	Stage 3	Stage 4
Clinical findings[a]	"Alert" from AVPU	"Verbal" from AVPU	"Painful" or "Unconscious" from AVPU Vital signs present	"Unconscious" from AVPU **AND** No detectable vital signs[b]
Risk of cardiac arrest[c]	Low	Moderate	High	Hypothermic cardiac arrest

[a] In the revised Swiss system, Alert corresponds to a Glasgow Coma Scale (GCS) score of 15; verbal corresponds to a GCS score between 9 and 14, including confused patients; and painful or unconscious corresponds to a GCS score below 9. While shivering is not used as a stage-defining criterion, its presence typically indicates a core temperature above 30 °C, at which hypothermic cardiac arrest is unlikely

[b] No respiration, no palpable carotid or femoral pulse, and no measurable blood pressure indicate cardiac arrest. In such cases, signs of life—including pulse and, particularly, respiration—should be checked for up to 1 min

[c] The transition of colours between stages illustrates the overlap between patient groups. The estimated risk of cardiac arrest assumes that accidental hypothermia is the sole cause of the clinical presentation. If other conditions affecting consciousness are present, such as asphyxia, intoxication, high-altitude cerebral oedema, or trauma, the system may overestimate the risk of hypothermic cardiac arrest. Caution is warranted if an alert or verbal patient shows haemodynamic or respiratory instability (e.g., bradycardia, bradypnoea, or hypotension), as this may indicate progression to a stage associated with higher cardiac arrest risk

of the degree of hypothermia and the risk of hypothermia-induced cardiac arrest.

29.2 Differential Diagnosis

29.2.1 Unconscious Hypothermic Patients

In cases of impaired consciousness, other causes—such as trauma, acute medical illness, exhaustion, or altitude sickness—should be considered, but hypothermia must not be overlooked (Fig. 29.2).

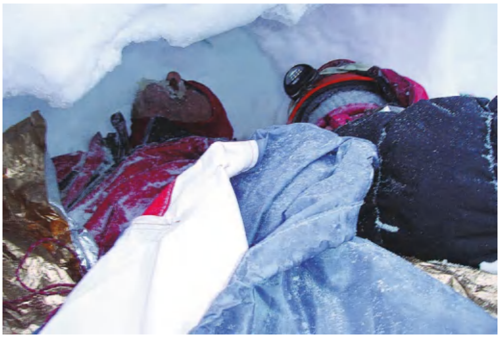


Fig. 29.2 Two unconscious hypothermic patients in an emergency bivouac after a stormy night at 4000 m above sea level. (Image rights: B. Durrer)

29.2.2 Lifeless Hypothermic Patients

In cases of cardiac arrest, it is not possible to distinguish "dead or apparently dead" at the scene without additional aids. Only if, in the case of an avalanche accident, the burial time exceeds 60 min and the patient presents with asystole and obstructed airways, or the body is completely frozen, or there are clearly fatal injuries or signs of decomposition, may the emergency physician refrain from resuscitation or terminate it at the scene (Lugnet et al. 2023).

Before any declaration of death, the physician must exclude potentially reversible hypothermia with cardiac arrest.

The emergency physician also bears significant responsibility towards the rescuers. Unwarranted resuscitation or passive evacuation of patients who are still able to walk exposes rescuers to unnecessary risks in hazardous terrain. In cases involving multiple hypothermic patients with cardiac arrest, the emergency physician must also perform rapid and reliable triage to determine priorities for care and transport.

If intoxication is suspected, the declaration of death should be made with particular caution, even in warmer environments.

Children cool rapidly in icy water and may survive underwater for more than 60 minutes without neurological damage (Bolte et al. 1988; Romlin et al. 2015).

In avalanche accidents, an unwitnessed cardiac arrest is usually due to asphyxia rather than hypothermia. In snow, an avalanche victim typically cools at a mean rate of 3–4 °C per hour, so with a burial time of less than 60 minutes, severe hypothermia (< 30 °C) is generally not expected (Pasquier et al. 2023).

29.2.3 Dead or Apparently Dead?

29.2.3.1 Clinical Signs

- **Fatal Injuries**

In the case of clearly fatal injuries, hypothermia is a secondary event and resuscitation should not be initiated.

- **Rigor Mortis/Cold Stiffening**

Rigor mortis is considered a reliable sign of death only at warm temperatures. There are documented cases of successful resuscitation in which both intubation and chest compressions were hampered by cold stiffening. However, for effective resuscitation, the thorax must be compressible. If the body is rigidly frozen, current knowledge allows for death to be declared at the scene (Durrer et al. 2001).

- **Post-mortem Lividity**

Post-mortem lividity can be very difficult to distinguish from pressure marks caused by positioning, even for experienced physicians in the field, and—like rigor mortis—should not be considered a reliable sign of death in lifeless hypothermic patients (Schön et al. 2020).

29.2.3.2 Core Temperature

Core Temperature Measurement

In the presence of circulation, CT can only be reliably measured at the tympanic membrane (epitympanic) if the ear canal is insulated from the outside. Various thermometers are available on the market, which can be used autonomously or in conjunction with a monitor, and more recently even in combination with mobile phones. In the absence of circulation, oesophageal measurement is recommended, as the epitympanic temperature may be falsely low (Walpoth et al. 1994; Strapazzon et al. 2014). The tip of the oesophageal probe should be positioned in the lower third of the oesophagus, posterior to the heart (Roveri et al. 2025). The lowest core temperature recorded in successful rewarming was 13.7 °C in an adult (Gilbert et al. 2000) and 11.8 °C in a young child (Mroczek et al. 2020). To avoid precluding future successful resuscitations at even lower temperatures, no minimum core temperature for hypothermia reversibility is deliberately set.

29.3 Measures at the Emergency Site

29.3.1 General Treatment

> In the field, rewarming severely hypothermic patients is challenging; preventing additional heat loss is critical.

To prevent further cooling, multi-layer insulation should be used.

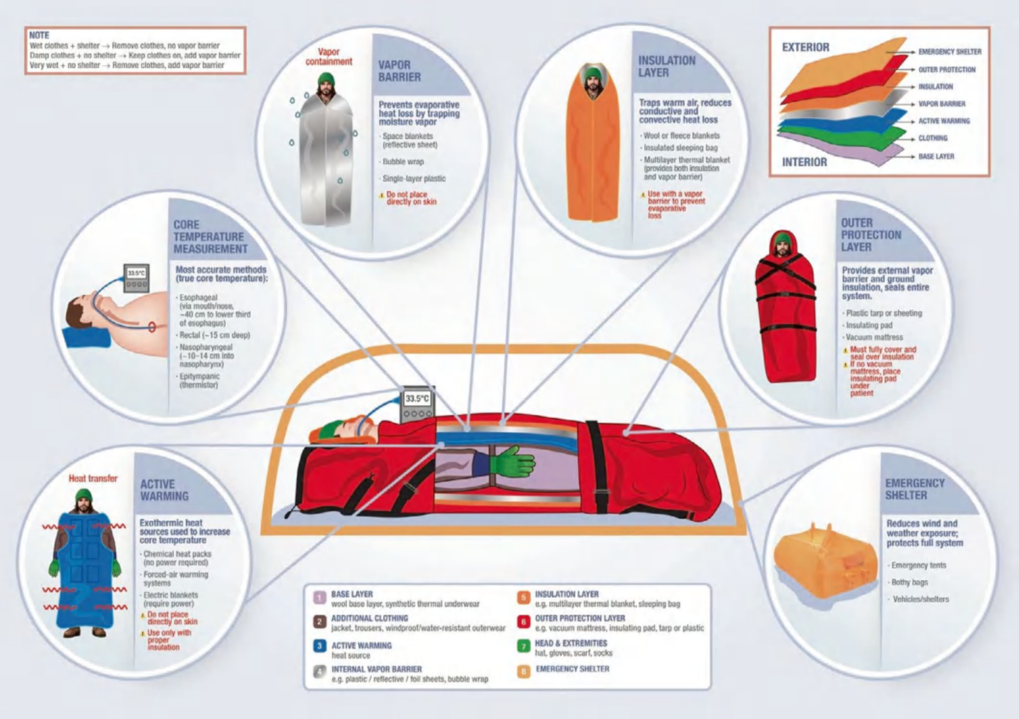
A schematic of the recommended layering system and temperature measurement methods for prehospital management of accidental hypothermia is shown in ◘ Fig. 29.3. Continuous ECG monitoring is also advised. Hospital admission may be omitted if hypothermia is mild, the patient is fully responsive, and injuries can be excluded. In all other cases, especially in critically buried avalanche victims, inpatient observation is recommended (Sumann et al. 2012).

29.3.2 Stage I (Mild Hypothermia)

- Allow active movement if this is safe and without risk.
- Administration of warm, carbohydrate-rich drinks.
- Administration of medication for the treatment of associated injuries intravenously, intraosseously, buccally, or nasally ("mucosal atomisation device").

29.3.3 Stage II (Moderate Hypothermia)

- Careful, low-movement rescue, horizontal positioning. Caution: potential risk of "rescue collapse"!
- Administration of oxygen (preferably humidified and warmed).
- Full-body insulation to prevent further cooling (◘ Fig. 29.3).


NOTE
Wet clothes + shelter → Remove clothes, no vapor barrier
Damp clothes + no shelter → Keep clothes on, add vapor barrier
Very wet + no shelter → Remove clothes, add vapor barrier
Vapor containment
VAPOR BARRIER
Prevents evaporative heat loss by trapping moisture vapor
· Space blankets (reflective sheet)
· Bubble wrap
· Single-layer plastic
Do not place directly on skin
INSULATION LAYER
Traps warm air, reduces conductive and convective heat loss
· Wool or fleece blankets
· Insulated sleeping bag
· Multilayer thermal blanket (provides both insulation and vapor barrier)
Use with a vapor barrier to prevent evaporative loss
EXTERIOR
INTERIOR
EMERGENCY SHELTER
OUTER PROTECTION
INSULATION
VAPOR BARRIER
ACTIVE WARMING
CLOTHING
BASE LAYER
CORE TEMPERATURE MEASUREMENT
Most accurate methods (true core temperature):
· Esophageal (via mouth/nose, ~40 cm to lower third of esophagus)
· Rectal (~15 cm deep)
· Nasopharyngeal (~10–14 cm into nasopharynx)
· Epitympanic (thermistor)
33.5°C
OUTER PROTECTION LAYER
Provides external vapor barrier and ground insulation, seals entire system.
· Plastic tarp or sheeting
· Insulating pad
· Vacuum mattress
Must fully cover and seal over insulation
If no vacuum mattress, place insulating pad under patient
Heat transfer
ACTIVE WARMING
Exothermic heat sources used to increase core temperature
· Chemical heat packs (no power required)
· Forced-air warming systems
· Electric blankets (require power)
Do not place directly on skin
Use only with proper insulation
EMERGENCY SHELTER
Reduces wind and weather exposure; protects full system
· Emergency tents
· Bothy bags
· Vehicles/shelters
1 BASE LAYER wool base layer, synthetic thermal underwear
2 ADDITIONAL CLOTHING jacket, trousers, windproof/water-resistant outerwear
3 ACTIVE WARMING heat source
4 INTERNAL VAPOR BARRIER e.g. plastic / reflective / foil sheets, bubble wrap
5 INSULATION LAYER e.g. multilayer thermal blanket, sleeping bag
6 OUTER PROTECTION LAYER e.g. vacuum mattress, insulating pad, tarp or plastic
7 HEAD & EXTREMITIES hat, gloves, scarf, socks
8 EMERGENCY SHELTER

◘ **Fig. 29.3** Recommended prehospital layering and temperature measurement in accidental hypothermia. The figure illustrates the recommended insulation sequence from internal to external layers: (1) base layer (thermal underwear); (2) protective clothing (jacket, trousers, waterproof layers); (3) active warming (e.g. chemical packs); (4) internal vapour barrier (foil, bubble wrap); (5) insulation layer (thermal blanket, sleeping bag); (6) outer protection (vacuum mattress, tarp); (7) head and extremity covering (hat, gloves, socks); and (8) emergency shelter (tent, bothy bag, vehicle). (From Leuci et al. 2025)

- Transfer to a hospital with the capability for active external rewarming using warm air (Kornberger et al. 1999).

Parenteral or buccal/nasal medication is generally only indicated in the presence of additional comorbidities or injuries. From approximately 30 °C core temperature, the effect of medication is delayed or absent due to centralisation of the circulation.

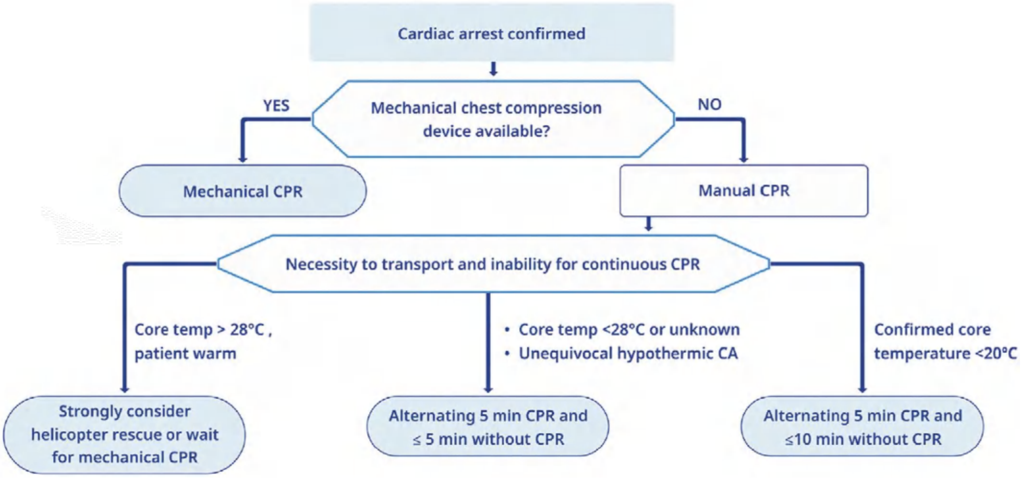
29.3.4 Stage III (Severe Hypothermia)

In addition to the measures in Stage II:

- Airway management if necessary and, if possible, ventilation with (warm, humidified) oxygen. Otherwise, place the patient in the recovery position and ensure close monitoring during transport.
- Avoid prolonged medical interventions in the field to prevent further cooling. The risk of cardiac arrest increases significantly at a CT of 28 °C.
- In cases of haemodynamic instability (systolic blood pressure < 90 mmHg, ventricular arrhythmias, CT < 30 °C), the target hospital should be a centre with the capability for extracorporeal rewarming (Lott et al. 2025).

29.3.5 Stage IV (Hypothermic Cardiac Arrest)

Endotracheal intubation and CPR should be continued until arrival at the target hospital. Maintaining high-quality chest compressions is difficult or even impossible in rough terrain and during transport in confined spaces (Odegaard et al. 2009; Putzer et al. 2012). Where possible, mechanical resuscitation devices (e.g. LUCAS® or Autopulse®) should be used to improve the continuity and quality of chest compressions (Putzer et al. 2012). If continuous CPR cannot be performed, intermittent CPR may be considered in severely hypothermic patients to enable transport across difficult terrain: For patients with a CT < 28 °C, 5 min of CPR can be alternated with ≤ 5 min without CPR; if CT < 20 °C, 5 min of CPR can be alternated with ≤ 10 min without CPR (Gordon et al. 2015) (▣ Fig. 29.4).


Cardiac arrest confirmed
YES
Mechanical chest compression device available?
NO
Mechanical CPR
Manual CPR
Necessity to transport and inability for continuous CPR
Core temp > 28°C , patient warm
• Core temp <28°C or unknown
• Unequivocal hypothermic CA
Confirmed core temperature <20°C
Strongly consider helicopter rescue or wait for mechanical CPR
Alternating 5 min CPR and ≤ 5 min without CPR
Alternating 5 min CPR and ≤10 min without CPR

▣ **Fig. 29.4** Delayed and intermittent CPR in hypothermic patients when continuous CPR is not possible during dangerous or difficult rescue. (Adapted from Lott et al. 2025). *CPR* cardiopulmonary resuscitation, *HEMS* helicopter emergency medical service/air ambulance

- The use of ALS drugs in hypothermic patients is controversial (Krismer et al. 2000; Kornberger et al. 2001; Stoner et al. 2003; Lott et al. 2025). At a CT of <30 °C, antiarrhythmics (e.g. amiodarone) and sympathomimetics (e.g. adrenaline or noradrenaline) are not recommended; at a CT of 30–35 °C, it is recommended to extend the dosing interval of these drugs (Lott et al. 2025).
- Shockable rhythms: A maximum of three defibrillation attempts with maximum energy. If defibrillation is unsuccessful, resuscitation should not be discontinued but continued until rewarming is achieved. Defibrillation is generally successful at a CT > 30 °C (Lott et al. 2025) but may also succeed at lower temperatures in individual cases (Mair et al. 2019).
- A patient with hypothermic cardiac arrest should be transported to a hospital with extracorporeal life support (ECLS) capability, ideally veno-arterial extracorporeal membrane oxygenation (VA-ECMO), for rewarming (Walpoth et al. 1997; Brown et al. 2012; Paal et al. 2016; Lott et al. 2025). The target hospital should be contacted as early as possible to confirm capacity for admission. If this is not possible within 6 h, combined external (warm air) and internal invasive rewarming (thoracic or peritoneal lavage) should be attempted in a closer hospital under ongoing CPR.

29.3.6 Target Hospital

The choice of target hospital can be decisive for patient outcome and depends on the severity of hypothermia, comorbidities, and transport options. Hypothermic patients should be transferred rapidly and gently—preferably by helicopter—to a hospital equipped with specialised personnel and technology for optimal hypothermia management. Early notification to activate the rescue chain and, if necessary, the ECLS team is essential.

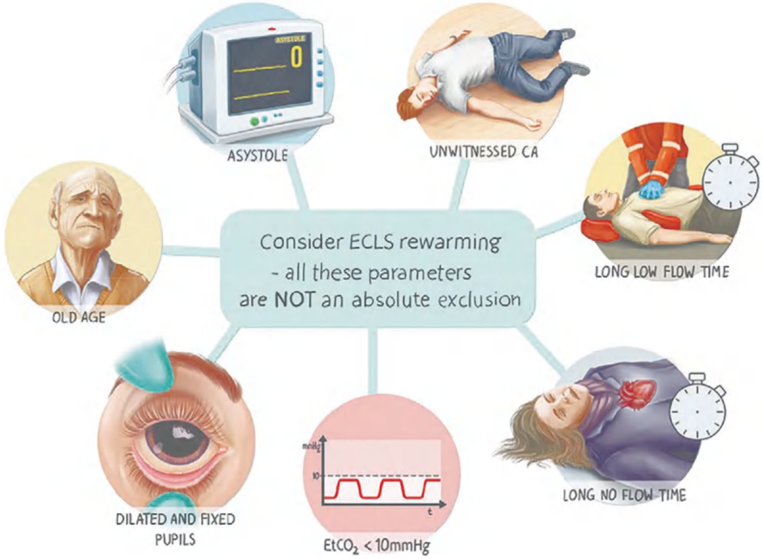
29.4 Outcome

> Due to the neuroprotective effect of hypothermia, hypothermic cardiac arrest can be survived with a good neurological outcome even after prolonged cardiac arrest and extended resuscitation.

The longest documented CPR in hypothermic cardiac arrest to date is just under 9 h (Forti et al. 2018). The best prognosis is seen when hypothermic cardiac arrest is not preceded by hypoxia and there are no significant comorbidities. No single clinical finding or laboratory value allows for a reliable prediction of prognosis. Asphyxia, which often occurs in the context of avalanche burial or drowning, is associated with a poor prognosis, especially when accompanied by hyperkalaemia. Absence of asphyxia, rapid cooling, and normal serum potassium are associated with a favourable prognosis. Prognostic assessment of successful extracorporeal rewarming in hypothermic patients with cardiac arrest should be performed using the HOPE Score (▶ https://www.hypothermiascore.org) (Pasquier et al. 2018, 2019).

If cardiac arrest is clearly due to another cause and not hypothermia, such as asphyxia or multiple trauma, prolonged resuscitation is not appropriate. In the case of unsurvivable injuries, CPR should be withheld (Paal et al. 2012). In all other cases, the guiding principle remains: “No one is dead until warm and dead” (Brugger et al. 2001).

> Accidentally hypothermic patients have good chances of neurologically intact survival even in unwitnessed cardiac arrest and when asystole is the initial rhythm(Podsiadlo et al. 2021). It is important that hypothermia (core tempera-

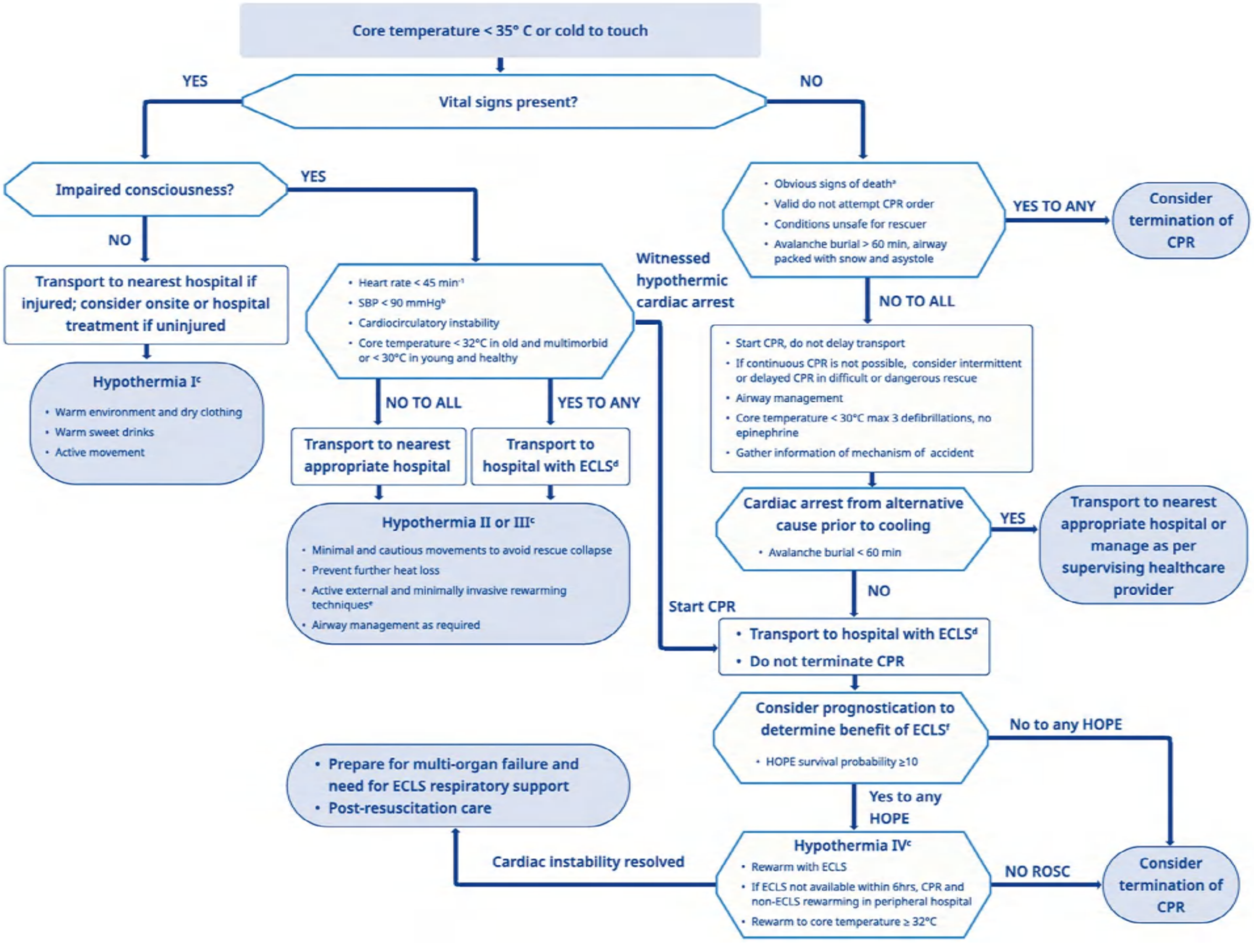

ASYSTOLE
0
ASYSTOLE
UNWITNESSED CA
LONG LOW FLOW TIME
OLD AGE
Consider ECLS rewarming
- all these parameters
are NOT an absolute exclusion
DILATED AND FIXED PUPILS
mmHg
10
t
$EtCO_2 < 10mmHg$
LONG NO FLOW TIME

◘ **Fig. 29.5** Criteria which, in contrast to normothermic patients with cardiac arrest, do not constitute a contraindication to extracorporeal resuscitation (ECLS) in hypothermic patients with cardiac arrest. (From Swol et al. 2022)

ture < 30 °C) occurred before cardiac arrest, as only then can the cold exert a protective effect (Swol et al. 2022). In hypothermic patients, a low end-tidal CO_2 is not an unfavourable prognostic sign, in contrast to normothermic patients (Darocha et al. 2022) and should not be used as a criterion for terminating CPR (◘ Fig. 29.5).

29.5 Treatment Algorithm

◘ Figure 29.6 illustrates the management of patients with accidental hypothermia.


Core temperature < 35° C or cold to touch
Vital signs present?
YES
NO
Impaired consciousness?
YES
NO
Transport to nearest hospital if injured; consider onsite or hospital treatment if uninjured
Hypothermia I^c
• Warm environment and dry clothing
• Warm sweet drinks
• Active movement
• Heart rate < 45 min^-1
• SBP < 90 mmHg^b
• Cardiocirculatory instability
• Core temperature < 32°C in old and multimorbid or < 30°C in young and healthy
NO TO ALL
YES TO ANY
Transport to nearest appropriate hospital
Transport to hospital with ECLS^d
Hypothermia II or III^c
• Minimal and cautious movements to avoid rescue collapse
• Prevent further heat loss
• Active external and minimally invasive rewarming techniques^e
• Airway management as required
Witnessed hypothermic cardiac arrest
Start CPR
• Obvious signs of death^a
• Valid do not attempt CPR order
• Conditions unsafe for rescuer
• Avalanche burial > 60 min, airway packed with snow and asystole
YES TO ANY
Consider termination of CPR
NO TO ALL
• Start CPR, do not delay transport
• If continuous CPR is not possible, consider intermittent or delayed CPR in difficult or dangerous rescue
• Airway management
• Core temperature < 30°C max 3 defibrillations, no epinephrine
• Gather information of mechanism of accident
Cardiac arrest from alternative cause prior to cooling
• Avalanche burial < 60 min
YES
Transport to nearest appropriate hospital or manage as per supervising healthcare provider
NO
• Transport to hospital with ECLS^d
• Do not terminate CPR
Consider prognostication to determine benefit of ECLS^f
• HOPE survival probability ≥10
No to any HOPE
Yes to any HOPE
Hypothermia IV^c
• Rewarm with ECLS
• If ECLS not available within 6hrs, CPR and non-ECLS rewarming in peripheral hospital
• Rewarm to core temperature ≥ 32°C
NO ROSC
Consider termination of CPR
Cardiac instability resolved
• Prepare for multi-organ failure and need for ECLS respiratory support
• Post-resuscitation care

◘ **Fig. 29.6** Management of accidental hypothermia. (**a**) Decapitation; truncal transection; whole body decomposed or whole body frozen solid (chest wall not compressible). (**b**) Systolic blood pressure < 90 mmHg is a reasonable prehospital estimate of cardiocirculatory instability, but for in-hospital decisions, the minimum sufficient circulation for a deeply hypothermic patient (e.g., <28 °C) has not been defined. (**c**) Swiss staging of accidental hypothermia. (**d**) Direct transport to an ECLS centre is recommended in an arrested hypothermic patient. In remote areas, transport decisions should balance the risk of increased transport time with the potential benefit of treatment in an extra corporal life support centre. Transfer should be commenced if such a centre can be reached within 6 h. (**e**) Warm environment, chemical, electrical, or forced-air heating packs or blankets, and warm IV fluids (38–42 °C). In case of cardiac instability refractory to medical management, consider rewarming with extra corporal life support. (**f**) If the decision is made to stop at an intermediate hospital to measure serum potassium, a hospital enroute to an extra corporal life support centre should be chosen. The HOPE score should not be used in children, consider expert consultation instead. *ECLS* extracorporeal life support, *ROSC* return of spontaneous circulation, *SBP* systolic blood pressure. (From Lott et al. 2025)

29.6 Practical Suggestions

The trained mountain rescue physician is familiar with the pathophysiology of hypothermia and is proficient in crevasse rescue techniques as well as the organisation of an avalanche accident site. They are aware that infusions and ampoules can freeze in the cold, batteries can discharge, and plastic components (such as endotracheal tubes) can become brittle and take appropriate precautions. On snowfields, especially in sunshine, intubation is performed under a blanket, waiting until the eyes have adapted to the relative darkness.

29.6.1 Protection Against Further Cooling

To prevent further cooling, a hypothermic patient should be taken immediately after rescue to a wind-sheltered location (snow cave, tent). Several layers of insulation should be applied (◘ Fig. 29.3) (Leuci et al. 2025; Henriksson et al. 2010). Wet clothing should only be removed if evacuation will be prolonged or is not possible. Chemical heat packs (placed on the torso, under the insulation) must always be insulated from the body (risk of burns). If a conscious patient can swallow without risk of aspiration, warm drinks are an efficient and valuable means of preventing further cooling. A thermos flask with hot, sweet tea should therefore be part of the alpine medical equipment at every mountain accident. The administration of humidified, warm oxygen (“airway warming”) can be another method to protect a patient from further cooling (Giesbrecht and Paton 1998).

29.6.2 “Stay and Play or Load and Go?”

Do not treat a hypothermic patient in the field with prolonged initial care, thereby risking progression to deeper hypothermia! The time required to treat a patient at the scene, with the risk of further cooling, must be weighed against the benefit to the patient. Every unnecessary minute spent in the cold increases the risk of hypothermia for the patient and—in the presence of objective mountain hazards—the risk to the rescue team.

> After stabilisation of vital functions, preventing further cooling during rescue and transport takes priority.

Conclusion

In the mountains, every casualty should be considered hypothermic until proven otherwise. This applies not only in cold winter conditions, but also at milder temperatures. The prognosis for severe hypothermia with cardiac arrest is especially favourable if hypothermia occurred before hypoxia. In such cases, hope should never be abandoned, and a destination hospital with ECLS should be chosen, as even prolonged resuscitation efforts lasting several hours do not preclude a good neurological outcome. Decisive and consistent action is required. Also in cases of unstable haemodynamics (systolic blood pressure < 90 mmHg, ventricular arrhythmia, core temperature < 30 °C), a hospital with ECLS should be selected. Patients with stable haemodynamics, on the other hand, can be actively rewarmed externally with warm air in peripheral hospitals without risk.

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Frostbite

Rosmarie Oberhammer, Elisabeth Gruber, and Emmanuel Cauchy

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Dr. E. Cauchy has sadly passed away.

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Frostbite is a local cold injury caused by the freezing of tissue, which can result in tissue loss and permanent impairment. The areas most affected are the hands, feet, nose and cheeks (Zafren 2013; Regli et al. 2021). In earlier times, frostbite was a typical wartime injury. The incidence of frostbite among armed forces in arctic regions decreased over a period of approximately 70 years (1942–2018) from 7 to 1% (van Dongen et al. 2023), presumably due to the absence of large-scale military manoeuvres and combat operations, as well as improved insulating clothing. During a smaller military exercise, the incidence of frostbite rose again to nearly 20% due to low ambient temperatures (−21°C) and wind chill (−44°C) (Sullivan-Kwantes et al. 2017). Female members of the US Army have a 1.5-fold higher risk; younger soldiers and inexperienced recruits are also at increased risk (Sullivan-Kwantes et al. 2017). The incidence of frostbite is now increasing among at-risk groups in the general population (Murphy et al. 2000). In Finland, 5.1% of 13,713 respondents reported having suffered frostbite at some point in their lives. The annual incidence for mild frostbite was 14.2% in men and 11.9% in women, and for severe frostbite 1.1% and 0.6%, respectively (Mäkinen et al. 2009).

Mountaineers are affected by frostbite at an above-average rate, with an annual incidence of 366 per 1000 (Harirchi et al. 2005), as are individuals who are occupationally or recreationally exposed to cold and windy conditions, those fleeing political conflict or natural disasters, or who are homeless for social reasons (Zafren 2013). Overall, however, clinically significant frostbite, with an incidence of 0.07/100,000, remains rare even in alpine regions of Europe (Ströhle et al. 2018).

30.1 Causes and Risk Factors

The main causes of frostbite are increased heat loss due to convection in windy conditions, conduction when the skin comes into contact with cold surfaces or cold water and reduced heat production (Zafren 2013). The severity of cold injuries increases with decreasing temperature below the tissue freezing point, duration of exposure, wind (Murphy et al. 2000) and length of cold exposure.

Permeable, poorly insulating, incompletely covering, damp or excessively tight clothing, as well as the application of oily protective creams, promote the development of frostbite (Lehmuskallio 2000). Additional risk factors are listed in ▣ Table 30.1 (Hallam et al. 2010; Haman et al. 2022; Harirchi et al. 2005; Koljonen et al. 2004; Olsen 2002; Armed Forces Health Surveillance Division 2026).

While body mass plays an important role as a risk factor for hypothermia, depending on the individual and subgroup, cold injuries with or without frostbite are primarily related to changes in peripheral blood flow and the associated drop in skin temperature (Haman et al. 2022). Individuals with the homozygous deletion polymorphism of the angiotensin-converting enzyme (ACE) gene are thought to be more prone to vasoconstriction and thus frostbite, especially at high altitude and in hypoxic conditions, due to increased ACE activity (Kamikomaki 2007). In contrast, a genetically determined ability for cold-induced vasodilation may have a protective effect (Daanen and van der Struijs 2005).

❯ There are numerous risk factors for the development of frostbite.

Table 30.1 Risk factors for frostbite

External risk factors	Individual risk factors	Other risk factors
– Temperature < –4 °C – Wind and wind speed – Humidity – Extreme altitude (> 5000 m) – Hypoxia – Traffic and recreational accidents	– Age and sex – Body composition, weight, skin pigmentation – Dehydration – Malnutrition – Alcohol, drug, nicotine abuse and use of specific medication (e.g. sedatives, beta-blockers, anti-hyperglycemics) – Psychiatric disorders – Diabetes mellitus – Vascular diseases (peripheral arterial occlusive disease [PAOD], Raynaud's disease) – Low educational attainment – Unemployment and homelessness – Cold sensitivity, previous cold injuries – Repeated vibration exposure of hands and arms (e.g. operating heavy machinery or use of snowmobiles, helicopters, etc.)	– Improper use of cold and ice packs, as well as nitrous oxide – Improper use of fire extinguishers or camping stoves

30.2 Pathophysiology

Four overlapping stages of frostbite can be distinguished:

- Pre-freeze phase,
- Freezing and thawing phase,
- Vascular stasis phase,
- Late ischaemic phase.

In the first phase, tissue cooling leads to vasoconstriction and ischaemia, and cold-induced nerve injury results in hyperaesthesia and paraesthesia. In the second phase, rapid freezing causes intracellular ice crystals to form, while slow freezing also leads to extracellular ice crystal formation. This is followed by cellular dehydration and electrolyte shifts, denaturation of proteins and fats, dissolution of cell membranes and ultimately cell death. During the thawing phase, ischaemic and reperfusion injuries occur, accompanied by inflammatory reactions. In the third phase, vasoconstriction and vasodilation alternate every 5–10 min (the so-called hunting reaction) (Dana Jr et al. 1969). The late ischaemic phase results from inflammation induced by thromboxane A2, prostaglandin F2-α, bradykinins and histamine. Vasoconstriction, thrombosis, and embolism in smaller and larger arterial and venous vessels ultimately damage both micro- and macrocirculation. Tissue injury is exacerbated by repeated cycles of thawing and refreezing (McIntosh et al. 2024; Regli et al. 2021).

The pathophysiology of long-term sequelae following frostbite remains largely unexplored. The TRP ("transient receptor potential") receptor family plays a role in the development of cold-induced allodynia. Cold-induced nerve injuries can lead to neuropathic pain and ischaemic neuritis. Cold-induced osteoarthritis may cause pain even years after a frostbite injury (Regli et al. 2021).

30.3 Clinical Presentation

Initially, the affected area appears pale and mottled, later becoming bluish-violet. The skin feels cold and at first soft, but later waxy, hard and numb. Occasionally, frostbite may develop without any warning signs,

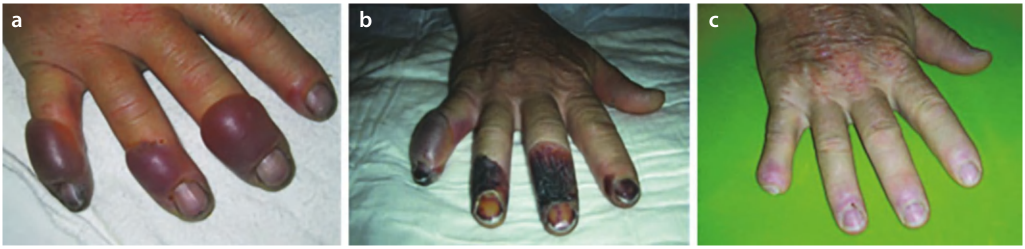


Fig. 30.1 a–c Frostbite of the hand at different time intervals

presenting as complete numbness. After thawing, the affected zone is clearly demarcated from healthy tissue and is referred to as the initial injury. If thawing occurs rapidly, local hyperaemia may develop. Blisters may form within the first hour or only days after thawing (Zafren 2013). Figure 30.1a–c shows frostbite of the hand at different time intervals.

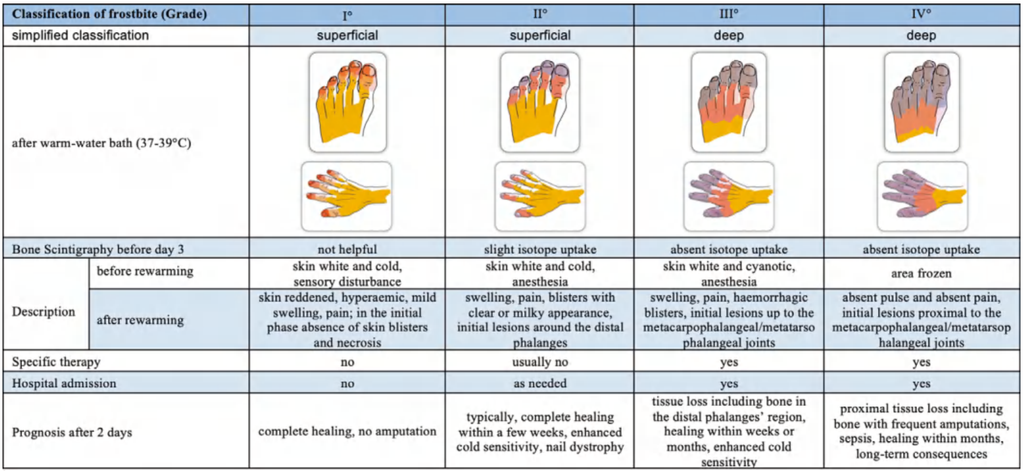
30.4 Classification and Prognosis

Similar to the classification used for burns, frostbite is graded I–IV. Classification on site prior to rewarming can be challenging, as the affected tissue is hard, pale and numb. The following classification after rewarming but before any imaging may be helpful (McIntosh et al. 2024):

- *Grade 1 frostbite*: numbness and erythema in the affected area, formation of a white or yellow, firm and slightly raised plaque. No tissue loss, mild desquamation of epidermal cells.
- *Grade 2 frostbite*: superficial skin blisters containing clear or milky fluid, with surrounding erythema and oedema.
- *Grade 3 frostbite*: haemorrhagic blisters involving the reticular dermis and the superficial venous plexus.
- *Grade 4 frostbite*: involvement of the entire dermis and subcutaneous tissue, with necrosis affecting muscles and bone.

A simpler scheme, which may be useful at the emergency site (prior to rewarming and before imaging) for rapid assessment and to determine whether urgent evacuation is necessary, distinguishes between *superficial* (corresponding to first- and second-degree frostbite) and *deep* frostbite (corresponding to third- and fourth-degree frostbite) (McIntosh et al. 2024).

To better predict the final extent of lesions and the likelihood of and level of amputation, Cauchy et al. (2001) described a classification of frostbite of the hands and feet based on bone scintigraphy and the extent of the initial lesions (Fig. 30.2).



Classification of frostbite (Grade)		I°	II°	III°	IV°
simplified classification		superficial	superficial	deep	deep
after warm-water bath (37-39°C)					
Bone Scintigraphy before day 3		not helpful	slight isotope uptake	absent isotope uptake	absent isotope uptake
Description	before rewarming	skin white and cold, sensory disturbance	skin white and cold, anesthesia	skin white and cyanotic, anesthesia	area frozen
	after rewarming	skin reddened, hyperaemic, mild swelling, pain; in the initial phase absence of skin blisters and necrosis	swelling, pain, blisters with clear or milky appearance, initial lesions around the distal phalanges	swelling, pain, haemorrhagic blisters, initial lesions up to the metacarpophalangeal/metatarso phalangeal joints	absent pulse and absent pain, initial lesions proximal to the metacarpophalangeal/metatarsop halangeal joints
Specific therapy		no	usually no	yes	yes
Hospital admission		no	as needed	yes	yes
Prognosis after 2 days		complete healing, no amputation	typically, complete healing within a few weeks, enhanced cold sensitivity, nail dystrophy	tissue loss including bone in the distal phalanges' region, healing within weeks or months, enhanced cold sensitivity	proximal tissue loss including bone with frequent amputations, sepsis, healing within months, long-term consequences

Fig. 30.2 Classification of frostbite. (Adapted from Cauchy et al. 2001)

30.5 Imaging

To rule out fractures and/or internal organ injuries, X-ray and/or computed tomography (CT) examinations should be performed. If the affected tissue appears bluish after rewarming, haemorrhagic blisters are present, and no pulse can be detected by Doppler sonography, digital subtraction angiography should be performed if available. This provides the best assessment of vascular perfusion at initial presentation and during follow-up, helps to define possible therapeutic goals and to evaluate the success of rtPA and/or iloprost therapy (Millet et al. 2016). In addition to bone scintigraphy, which is performed between the second and fourth day or, in case of unclear findings, again between the seventh and tenth day (Cauchy et al. 2000), a 99mTc-MDP bone scintigraphy with single-photon-emission CT-SPECT/CT enables precise delineation of lesions and prognostic determination of amputation lines (Manganaro et al. 2019).

30.6 Treatment

Since the 1930s, rapid rewarming, daily wound care, as-needed antibiotic prophylaxis or therapy, and expectant observation until demarcation have been the standard treatment for frostbite. 'Freeze in January and amputate in June' was a common adage. It was not until the 1990s that the use of thrombolytics and prostacyclin analogues led to improvements in the conservative management of severe frostbite, although a large-scale prospective randomised trial is still lacking. Most of the following recommendations for the prevention and treatment of frostbite are from the Wilderness Medical Society (McIntosh et al. 2024).

30.6.1 Prehospital Management

30.6.1.1 General Principles

'Treat first what kills first!'—According to this principle, life-threatening conditions such as hypothermia and trauma must be treated as a priority. The duration of tissue freezing should be kept as short as possible to minimise the risk of tissue damage. Frozen tissue must therefore be protected from further cold exposure and mechanical injury as quickly as possible. Any impairment of circulation, for example, by tight shoes, gloves or jewellery, should be avoided, and the affected tissue must never be rubbed or massaged.

As hypoxia is an independent risk factor and prognosis also depends on the severity of tissue ischaemia during the thawing phase, oxygen should be administered if available. This is particularly important if oxygen saturation is <90% and at altitudes above 4000 m. At this altitude, the use of portable hyperbaric chambers should also be considered.

Dehydrated patients should be given adequate fluids. If the patient is alert and does not complain of nausea or vomiting, warm drinks should be offered; otherwise (taking contraindications into account), warm intravenous fluids should be administered.

30.6.1.2 Rewarming

If there is no risk of refreezing, the affected tissue should be rewarmed as quickly as possible in a water bath at 37–39 °C in a warm, sheltered environment. To avoid scalding, the temperature should be checked with a thermometer or by a helper who immerses their hand in the water for at least 30 s.

To prevent further skin damage, the affected areas should be fully immersed in water without touching the sides of the container. The use of disinfectants during active rewarming cannot be generally recommended. Rewarming is complete once the frozen body part turns red or bluish and feels soft and pliable to the touch.

Depending on the severity of the frostbite, rewarming takes about 30–60 min. Rewarmed areas should be dried very carefully. If rapid rewarming in water is not possible, a frozen limb can also be rewarmed slowly and dry (e.g. in a heated tent or using body heat from oneself or others). If the risk of refreezing cannot be reliably excluded, no active rewarming is recommended.

30.6.1.3 Pain Management

As the frozen tissue thaws, patients often experience sharp, burning or electric-like pain. Acetylsalicylic acid is frequently used due to its additional antiplatelet effect, although supporting data are lacking. Ibuprofen is recommended for its anti-inflammatory properties, particularly in the first few days, at an oral dose of 6 mg/kg every 12 h. In cases of severe pain, opioids are additionally indicated. Peripheral nerve blocks may be beneficial for frostbite of the extremities, even in the pre-hospital setting, provided a careful risk-benefit assessment is undertaken (Pasquier et al. 2012).

Up to 50% of patients with frostbite develop chronic pain, with 15% experiencing severe pain, and some suffer from complex regional pain syndrome, a post-traumatic stress reaction with sleep disturbances and social limitations. Early, effective pain management and psychological support are therefore advisable (Koljonen et al. 2004; Regli et al. 2021).

30.6.1.4 Wound Management

Needle aspiration is only recommended for tense blisters filled with clear fluid that are at increased risk of rupture or perfusion impairment. Haemorrhagic blisters should be left intact wherever possible to prevent desiccation of the blister base. Aloe vera ointments may be helpful in reducing the formation of prostaglandins and thromboxane and should be applied to the affected area approximately every 6 h after rewarming. Wounds and blisters should be loosely covered with dry dressings (McIntosh et al. 2024).

30.6.2 In-Hospital Management

30.6.2.1 General Principles

In many respects, in-hospital care follows the same recommendations as pre-hospital management. The treatment of life-threatening comorbidities remains the highest priority. Active rewarming in a water bath is no longer indicated if the frozen tissue has already been rewarmed out of the hospital or has thawed passively, but may be appropriate if areas have not yet fully thawed.

After rewarming, medical staff should assess the severity using the table in ▪ Fig. 30.2. Blisters filled with clear or white fluid may be aspirated with a needle, while haemorrhagic blisters should remain intact. Ibuprofen is administered until complete wound healing or until surgical intervention. If tetanus immunisation is incomplete, tetanus prophylaxis should be provided.

Thromboprophylaxis is indicated in immobilised patients. Antibiotic prophylaxis is only recommended for higher-grade frostbite of the feet, particularly in patients with malnutrition, hepatic dysfunction, chronic alcohol abuse or following return from an expedition, to reduce the risk of local and systemic infections. Systemic antibiotic therapy, for example, with amoxicillin and clavulanic acid, may be necessary in individual cases. Hyperbaric oxygen therapy cannot currently be recommended, although isolated case reports and case series suggest a possible benefit (Zafren et al. 2024).

30.6.2.2 Vasodilators and Thrombolysis

Iloprost is a prostacyclin analogue with potent vasodilatory and antiplatelet effects, which reduces microcirculatory disturbances, decreases vascular permeability and induces fibrinolysis. In cases of higher-grade frostbite, it shows the greatest benefit within the first 24 h, and a positive effect has been demonstrated when therapy is initiated within the first 72 h after thawing (Regli et al. 2021).

Iloprost is administered intravenously within the first 48 h (possibly up to 72 h) at an initial dose of 0.5 ng/kg/min, increasing by 0.5 ng/kg/min every 30 min until side effects such as headache and hypotension occur, or up to a maximum of 2 ng/kg/min (Zafren et al. 2022). The established dose is then given for 5–8 days, each infusion lasting 6 h. In countries where iloprost is not available, alprostadil may be used at the standard dose.

Recombinant tissue plasminogen activator (rTPA) is used as a thrombolytic agent. Its use must be decided on a case-by-case basis, depending on the degree of frostbite, associated trauma, contraindications and the time elapsed (Cauchy et al. 2011). In third- or fourth-degree frostbite of a single extremity at high risk of significant, function-limiting amputations, intra-arterial rtPA should be administered. In cases involving two or more extremities, intravenous rtPA in combination with a low molecular weight heparin (e.g. enoxaparin) or unfractionated heparin should be administered as soon as possible within the first 24 h after rewarming (Zafren et al. 2024). Heparin is recommended as an adjunct, but not as monotherapy (Twomey et al. 2005).

In a randomised study in 2000, Cauchy could not exclude a possible additive effect from the combined administration of iloprost and rtPA in higher-grade frostbite.

> Vasodilators and thrombolytics may reduce the risk of tissue loss in severe frostbite if administered within the first 24 h.

30.6.2.3 Surgical Management

If a compartment syndrome or sepsis originating from the affected extremity develops after frostbite, immediate surgical intervention is required. Imaging techniques such as technetium-99 scintigraphy or 99mTc-MDP bone scintigraphy with SPECT/CT can be helpful in determining the required level of amputation. In the absence of compartment syndrome, sepsis or uncontrollable severe local infection, amputation should be delayed until complete demarcation occurs, usually after 1–3 months.

The patient should be managed by a multidisciplinary rehabilitation team. Sympathectomy is not recommended, even though it may prevent long-term sequelae such as pain, paraesthesia and hyperhidrosis in individual cases.

> As a rule, amputations should only be performed after definitive demarcation.

30.7 Prevention

The principle ‘prevention is better than cure’ is particularly relevant to frostbite. At-risk individuals should receive better training and supervision and should wear appropriate, well-insulated clothing, mittens, warm socks and footwear, protective goggles and face masks in cold conditions.

Moist or restrictive clothing or tight footwear, as well as excessively thick or multiple pairs of socks, should be avoided. On particularly cold days, double-insulated or vapour-barrier boots should be worn, and chemical or electric hand and foot warmers may be used. Good nutrition and adequate hydration are also important.

During prolonged cold exposure, it is advisable to take breaks to assess and warm the hands and feet. When in groups, participants should monitor each other to detect early signs of frostbite on the face. If fingers or toes are very cold or numb, or if the nose or ears appear white, these areas should be warmed; wet socks, gloves and other damp clothing should be removed and replaced with dry garments. In the field, in a tent or bivouac, it may be helpful to warm cold extremities in one’s own armpit, groin, abdomen or against the skin of a companion.

> **Conclusion**
>
> Prevention of frostbite is paramount. The management of life-threatening hypothermia and severe trauma takes priority. Rewarming and thawing should be avoided if refreezing cannot be ruled out. Rapid rewarming in a 37–39 °C water bath and subsequent dry wound covering are the most important initial measures. Patients with severe frostbite should be treated in a facility with appropriate expertise. Prompt surgical intervention is only necessary in exceptional cases; otherwise, amputation should be delayed until definitive tissue demarcation. Multidisciplinary team involvement is recommended for the prevention and management of long-term sequelae.

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Avalanche Medicine

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31.1 Introduction

Snow avalanches occur in steep, snow-covered terrain. They represent one of the most dangerous natural hazards in the mountains, particularly for winter sports enthusiasts who venture off-piste. Snow burials can also occur on secured ski slopes, in alpine settlements and on transport routes in the mountains. In Europe, the majority of snow burial fatalities occur in the Alpine countries of Switzerland, Austria, Italy and France, where avalanches have claimed an average of 85 lives per year over the past decade. In smaller European mountain ranges, such as the Pyrenees (approximately 10 deaths per year), the Norwegian-Swedish mountains (66 deaths in the last 10 years in Norway alone) and the Tatra between Poland and Slovakia, further fatalities occur each year as a result of avalanche burial (European Avalanche Warning Services 2023).

Within minutes of burial, the chances of survival decrease rapidly, making the fastest possible location and extrication of buried persons by companions crucial. For organised rescue services, the avalanche accident presents a particular challenge: as in other areas of prehospital emergency medicine, rescuer safety is the highest priority, especially in such inhospitable terrain. In an avalanche emergency, the situation is frequently complex and how extensive is the affected area can be unclear. Rapid, fundamental and far-reaching decisions regarding the course of rescue and treatment must be made. It is also not uncommon for several people to be buried simultaneously. In recent years, significant new insights have been gained in the areas of pathophysiology, prognostication and treatment. This chapter provides a state-of-the-art overview of avalanche burial and the rescue of avalanche victims.

31.2 Prevention

The prevention of avalanche accidents encompasses several levels. These include

- *Avoiding avalanche involvement.*
- *Preventing critical burial.*
- *Reducing traumatic injuries.*
- *Delaying asphyxia* following burial.

Recreational users trigger at least 90% of avalanches resulting in injury or death, and these are dry slab avalanches (Schweizer and Lütschg 2001; Techel et al. 2016). *Avoiding avalanche involvement* is the first and most important step towards safety in alpine snow terrain. Since the majority of avalanche accidents are triggered by winter sports enthusiasts themselves, there is considerable potential for prevention. Avalanche courses provide, amongst other things, essential knowledge about risk assessment and safe behaviour in the field. Knowledge of topography, weather forecasting, snow conditions and avalanche risk is crucial. Slopes with gradients between 30° and 45° are considered particularly prone to avalanches. Heavy snowfall, wind and rapid temperature rise further increase avalanche risk. Careful reading and monitoring of the daily avalanche bulletin are as essential as thorough tour planning. To maximise safety, avalanche warning services from various countries have joined forces to provide a joint, multilingual cross-border avalanche forecast, published on a shared website with a standardised workflow based on the standards of the European Avalanche Warning Services (EAWS) for avalanche forecasting (▶ https://avalanche.report/bulletin/latest). The website also provides maps of snow depth, fresh snow, air temperature, wind and gusts.

The *probability of being critically buried by an avalanche* can be reduced by avalanche airbags (Brugger et al. 2007). Avalanche airbags are backpacks or vests containing one or two inflatable balloons, which are manually activated by the user pulling a handle when caught in an avalanche. This inflates the balloons to a total volume of approximately 150 litres. Avalanche airbags use cylinders of compressed gas or a battery-powered fan for inflation. An inflated airbag increases the effective volume of an avalanche victim and utilises a physical process known as 'granular convection': in a flow of particles of varying sizes, larger particles are sorted to the surface (Gray and Ancey 2009), thereby reducing the likelihood of deep or complete burial. A retrospective study demonstrated a reduction in mortality from 22 to 11% with the use of an avalanche airbag (Haegeli et al. 2014). Regular practice in handling the device is essential to ensure the effectiveness of the avalanche airbag. In 20% of cases, the airbag was not deployed, with user error accounting for 60% of these incidents (Haegeli et al. 2014).

Regarding *prevention of trauma* in avalanche burial, helmets play a major role. They are widely used on ski slopes and can prevent or reduce the severity of traumatic brain injury (Haider et al. 2012). In the event of avalanche burial, helmets may be less effective, as the impact energy from obstacles in medium and large avalanches can exceed the protective ability of helmets (Vargyas 2016). Most avalanche fatalities occur in small to medium avalanches at lower speeds, where helmets could prevent traumatic brain injury (Boyd et al. 2010). Therefore, it is also generally recommended to wear a helmet when skiing off-piste. Avalanche airbags may also contribute to injury prevention. For example, some models are U-shaped and surround the head and neck when deployed. However, there are currently no studies demonstrating a reduction in the risk of traumatic brain or cervical spine injury as a result. In the future, it is expected that, due to climate change, the snowpack will become thinner and blunt trauma and secondary injuries from falls may become more frequent (Strapazzon et al. 2021).

For the *prevention or delay of asphyxia* following burial, a clear airway and the presence of an air pocket are crucial (Procter et al. 2016). The force of an avalanche can press snow into the mouth and nose of a victim. One possible technique to protect the airway is to place the arm over the face and the crook of the elbow over the mouth (Van Tilburg et al. 2017). In addition, devices have been developed to create an artificial air pocket (AAPD; artificial air pocket devices). An AAPD consists of a mouthpiece connected to a tube system containing a valve mechanism. The mouthpiece can help keep the airway free of snow. The valve mechanism locally separates exhaled air, which is rich in CO_2, from inhaled air, which is rich in oxygen. The inhaled air is drawn directly from the air within the snowpack, while exhaled air is directed towards the back. Two experimental studies have shown that the use of an AAPD can prolong the time to onset of hypoxaemia or hypercapnia (Grissom et al. 2000; Strapazzon et al. 2023). There are positive case reports on AAPDs (Crowley et al. 2002); however, studies comparing the mortality of users and non-users of an AAPD are lacking. Another method to create an artificial air pocket involves releasing the air from the inflated airbag. The resulting space could be used as an air pocket and delay asphyxia (McIntosh et al. 2020). However, there are no real-world studies on this approach yet either.

It has been shown that supplying air via a tube in front of the face of volunteers buried in a simulated avalanche leads to higher arterial oxygen saturation (SaO_2) and lower end-tidal carbon dioxide ($EtCO_2$) compared to the absence of air supply (Wik et al. 2022). Based on this, a device was developed that generates an airflow using a blower and tubing system, directing it towards the mouth and nose via the shoulder straps of the rucksack.

The effectiveness of this device has been demonstrated in a randomised controlled clinical trial (Eisendle et al. 2025). This trial demonstrated that delivering airflow from avalanche debris towards victims' airways delays hypoxaemia and hypercapnia, shifting CO_2 away and increasing oxygen supply for at least 35 min during a critical burial (Eisendle et al. 2025).

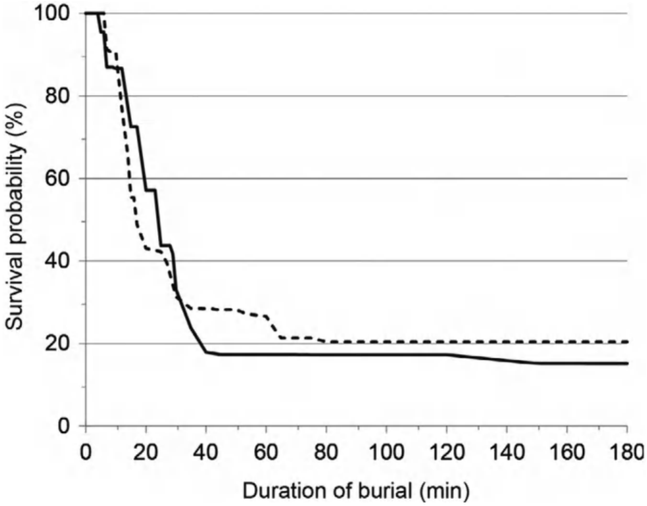
Overall, the prevention of avalanche accidents requires a combination of education, information, correct behaviour and appropriate equipment. Raising awareness of avalanche hazards, avoiding avalanche-prone terrain, practising safety techniques and using innovative protective equipment are crucial to minimising the risk of avalanche burial. Ongoing research into avalanche burial prevention will further contribute to improving safety.

31.3 Pathophysiology of Avalanche Accidents

The degree of burial is closely linked to survival. A distinction is made between 'critical burial' (i.e. the head and chest are buried in the snow) and 'non-critical burial' (the head and chest are not buried in the snow) (Pasquier et al. 2023). Ninety-six percent of non-buried or partially buried victims were still alive at the time of rescue, compared to 48% of critically buried victims (Haegeli et al. 2011; Pasquier et al. 2023). The morbidity and mortality of a critically buried avalanche victim largely depend on associated injuries, the duration of burial, the presence of an air pocket, the size of the air pocket, snow density and the depth of burial. An air pocket is defined as a snow cavity in front of the mouth and nose with unobstructed airways (mouth and nose are free) (Brugger et al. 2007, 2003; Haegeli et al. 2011; Paal et al. 2013).

In avalanche accidents death can be caused by trauma, asphyxia and hypothermia. The combination of these causes of death is highly specific to avalanche accidents and determines the particular pathophysiology of avalanche burial. ◘ Figure 31.1 shows survival following avalanche burial.

The following section describes the three causes of death in avalanche burial.



◘ **Fig. 31.1** Avalanche survival curve for Austria *(solid line)* and Switzerland *(dashed line)* for critically buried avalanche victims between 2005 and 2013. (Procter et al. 2016)

1. Trauma

Between 5% and 29% of avalanche victims die from traumatic injuries (Pasquier et al. 2023). Death from trauma usually occurs in the initial phase after avalanche burial. The topography of the accident site and the characteristics of the avalanche snow are key determinants of the injury pattern. For example, the risk of fatal trauma from impact with a hard obstacle is much higher in steep terrain with rocks or trees than in open terrain without obstacles (Hohlrieder et al. 2007). Spring snow is heavier and has more kinetic energy, so the likelihood of trauma is higher than in mid-winter with powder snow. Avalanche-related injuries most commonly affect the head, cervical spine, thorax and extremities (Hohlrieder et al. 2007). In cases of head injury and impaired consciousness, the probability of death from asphyxia increases (Johnson et al. 2001). Blunt trauma is the norm.

2. Asphyxia

Asphyxia is responsible for 65–100% of all avalanche fatalities. In cases of critical burial, the probability of survival is highly time-dependent, and the time to extrication is a decisive factor for survival (Falk et al. 1994; Pasquier et al. 2023; Procter et al. 2016). If the avalanche victim is rescued within the first 15–20 min, the survival rate is still around 90%. Thereafter, the probability of survival decreases rapidly and, after 35 min of burial, is only about 30% (‘asphyxia phase’, 18–35 min after critical burial). The main cause of death in this second phase is asphyxia. Asphyxia occurs during avalanche burial due to airway obstruction by snow or the absence of an air pocket. Other causes of asphyxia include the transformation of the snow in the air pocket by warm exhaled air, leading to sealing of the air pocket and reduced gas exchange with the surrounding snow, restriction of thoracic expansion due to the weight of the snow and progressive hypoxia caused by rebreathing exhaled air that is low in O_2 and high in CO_2.

The onset of asphyxia depends directly on the characteristics of the air pocket and the properties of the surrounding snow (Strapazzon et al. 2017). The larger the volume of the air pocket, the longer the potential survival time after avalanche burial. A larger air pocket provides a greater surface area for gas exchange with the surrounding snow, allowing exhaled CO_2 to diffuse from the air pocket into the snowpack and O_2 to diffuse from the snowpack into the air pocket. The density and permeability of the snow surrounding the air pocket are important factors for the diffusion of these gases (Grissom et al. 2000; Strapazzon et al. 2017). If the air pocket is large enough and the airways are clear, suffocation is delayed, and an avalanche victim may survive for up to 90 min (‘latency phase’, 35–90 min after burial) (Brugger et al. 2003; Grissom et al. 2004; Haegeli et al. 2011; Procter et al. 2016). If the air pocket communicates with the ambient air, it is referred to as an open-air pocket, and survival for many hours is possible without suffocation, although there is a risk of developing life-threatening hypothermia (Gruber et al. 2023).

3. Hypothermia

Accidental hypothermia is the primary cause of death in only about 4% of critically buried avalanche victims, as death from trauma or asphyxia usually occurs before death from hypothermia (Pasquier et al. 2023). The average cooling rate during avalanche burial, rescue and transport to a hospital is approximately 3 °C/h (Locher and Walpoth 1996). The individual rate of cooling varies between 0.1 and 9 °C/h and depends on various factors (Mittermair et al. 2021). The highest cooling rates have been measured, for example, in trained athletes ascending with only a thin layer of clothing, without gloves or hat, whilst the lowest rates were observed in robust skiers descending, fully equipped with multilayer clothing, helmet and gloves (Mittermair et al. 2021). In a few extreme cases, cooling to below 30 °C is possible in less than 60 min, resulting in hypothermia-induced cardiac arrest (Boyd et al. 2010; Eidenbenz et al. 2021; Lott et al. 2021; Rauch et al. 2023). Isolated case reports of very rapid cooling to core body temperatures that can lead to hypothermic cardiac arrest have been published (Pasquier et al. 2015; Rauch et al. 2023). The rate of cooling can be significantly higher outside the protective snow cave under very adverse conditions, such as cold ambient air and strong winds, than within the snow (Grissom et al. 2010, 2008). Due to the insulating properties of snow, the temperature within the snowpack is usually only slightly below 0 °C.

An avalanche accident can be survived for a surprisingly long time if the right factors are present. ◘ Table 31.1 presents the most extreme avalanche survival cases published to date. Recently, the third-longest avalanche burial ever survived was reported (Wallner et al. 2024). To improve understanding and management of these rare emergencies, it is important to collect data in international registries, for example, for avalanche burial (▶ https://www.mountain-registries.org) and accidental hypothermia (▶ https://hypothermia-registry.org).

◘ **Table 31.1** The most extreme avalanche accidents published to date. (Modified from Pasquier et al. 2023)

	Details of avalanche accident/publication
Non-cardiac arrest victims	
Longest burial times for survivors (burial in open terrain)[a]	43 h 45 min (Italy, female, age unknown, 1972) (de Quervain et al. 1973) 3 h (Italy, male, 2023) (Gruber et al. 2023) 25 h 30 min (Canada, 59 years, male, 1960) (Radwin and Grissom 2002) 17 h (Switzerland, 21-year-old male, 2010) (Eidenbenz et al. 2021)
Longest burial time for survivors (inside a building)	37 days (Italy, two women and an 11-year-old child buried in a 2 × 3 m cavity within a building) (Parry-Jones and Parry-Jones 1994)
Cardiac arrest victims	
Shortest burial duration resulting in cardiac arrest due to asphyxia and death	10 min (France, 29-year-old male, no airway obstruction, no air pocket, extricated in cardiac arrest) (Boué et al. 2014a) 10 min (Switzerland, age and sex not specified) (Brugger and Falk 1992)
Longest burial duration resulting in asphyxia-induced cardiac arrest with subsequent ROSC and survival	45 min (France, 39 years, male, unfavourable CPC) (Boué et al. 2014a) 20 min (France, 33-year-old male, 44-year-old male and 23-year-old male, all ROSC on site, all with unfavourable CPC) (Boué et al. 2014a) 20 min (United Kingdom, 32 years, sex unknown, burial duration 20 min, chest compressions, ROSC, CPC 1) (Gray 1987) 20 min (Austria, 26-year-old male and 31-year-old male, both prehospital ROSC and CPC 4) (Moroder et al. 2015)
Shortest burial duration leading to cardiac arrest before hypothermia and survival	100 min (Italy, 29 years, male, air pocket, witnessed cardiac arrest [VF], 21.7 °C, potassium 4.3 mmol/l, ECMO, CPC 1) (Oberhammer et al. 2008)

(continued)

Table 31.1 (continued)

	Details of avalanche accident/publication
Longest burial duration resulting in cardiac arrest due to asphyxia, ROSC and death	60 min (France, 29 years, male, 15 min CPR, prehospital ROSC) (Boué et al. 2014a) 60 min (Austria, 53 years, sex unknown, prehospital ROSC) (Gasteiger et al. 2022) 60 min (Italy, 41 years, male, ROSC after ECLS, organ donor) (Varutti et al. 2019)
Longest burial duration resulting in cardiac arrest due to hypothermia and survival	7 h (France, 41 years, male, witnessed cardiac arrest [PEA], ECLS, CPC 1) (Boué et al. 2014b)
Longest CPR duration in a survivor	5 h 45 min (Poland, 25 years, female, burial duration 2 h, witnessed cardiac arrest [VF], ECLS, CPC 1) (Kosinski et al. 2016)
Longest CPR duration resulting in prehospital ROSC	148 min (France, 51 years, female, burial duration 30 min, asystole, potassium 4.7 mmol/l, deceased) (Boué et al. 2014a) 100 min (France, 41 years, female, burial duration 40 min, PEA, ROSC, potassium 10.4 mmol/l, deceased) (Boué et al. 2014a)
Highest potassium level in a survivor of avalanche burial rewarmed with ECLS	6.4 mmol/L (Switzerland, age and sex unknown, witnessed cardiac arrest, burial duration 120 min, 24.2 °C, CPR duration 108 min, CPB, CPC 1) (Locher and Walpoth 1996)

[a] Case report of a victim recovered after a 6-day burial. The victim later died from trauma (India, 33 years old, male) (Dwivedi et al. 2016)

CPB cardiopulmonary bypass; *CPC* cerebral performance category; *CPR* cardiopulmonary resuscitation; *ECLS* extracorporeal life support; *ECMO* extracorporeal membrane oxygenation; *PEA* pulseless electrical activity; *ROSC* return of spontaneous circulation; *VF* ventricular fibrillation

31.4 Mortality and Morbidity in Avalanche Accidents

If the rescue of the buried person from the snow is achieved within 15 min, survival is highly likely at >90% (Pasquier et al. 2023). This underscores the importance of regular training in avalanche rescue procedures and the use of avalanche rescue equipment, i.e. avalanche transceiver, probe and shovel, to ensure efficient and rapid location and extrication. Extrication time is directly proportional to the depth of burial and is approximately 10 min for a *depth of burial* of 1 m (Wallner et al. 2019).

> A tour partner trained in avalanche rescue is the best life insurance, as they can enable rapid location and extrication of the buried partner within the critical first 15 min, before the arrival of professional rescue services.

In the subsequent phase of burial (‘latency phase’, 15–90 min after burial), the airway status and the presence of an air pocket are of utmost importance. If the airway remains clear after burial and also there is a sufficiently large air pocket, survival is possible even with burial durations of up to 90 min. The formation of an air pocket and the ability to breathe following avalanche burial, as well as the diffusion of gases through the snow, are directly dependent on the physical properties of the snow (including snow density). Although hypothermia also has a direct impact on mortality and morbidity in avalanche accidents, it is now known that most avalanche victims experience cardiac arrest while normothermic and only cool down afterwards. Consequently, the chances of survival with a favourable neurological outcome are unfortunately poor (Boué et al. 2014a; Moroder et al. 2015). In any case, hypothermia must be considered as a possible cause of cardiac arrest in cases of burial lasting 60 min in combination with clear airways not obstructed by snow. In such cases, cardiopulmonary resuscitation (CPR) should be performed (Lott et al. 2025). Hypothermic cardiac arrest may also be considered at the discretion of the rescuer in cases of burial of ≤60 min in a victim with a clear airway and no vital signs, if there is a possibility of very rapid cooling due to inadequate clothing, a slender body habitus, an environment conducive to rapid cooling or burial following physical exertion (Mittermair et al. 2021). Only a few avalanche victims survive burial for longer than 2 h ("long-term survival phase"). Survival after such a prolonged burial appears to be possible only in the presence of an air pocket that is connected to the ambient air, as only three survivors without an air pocket after 20, 25, and 120 min have been documented in the literature to date. Although low-density snow may facilitate continuous O_2 supply and CO_2 buffering, sustained adequate gas exchange is essential for long-term survival (Strapazzon et al. 2017; Wik et al. 2022). Understanding this time-critical progression of survival probability following critical burial is crucial for decision-making in the context of an avalanche accident. In addition, there are several disease and injury patterns specific to avalanche burial, which will be discussed in more detail in the following sections.

31.4.1 Frostbite

A particular type of trauma, which occurs especially in cases of partial burial, is frostbite. While body regions covered by snow are relatively well protected from cold exposure due to the insulating properties of snow, frostbite of body parts protruding from the snow can, although rare, represent a possible complication of avalanche accidents during prolonged burial. Low temperatures, exacerbated by wind and moisture, can lead to frostbite, particularly on exposed areas such as the extremities. Accidental hypothermia accelerates the onset of frostbite, especially after shivering ceases. Frostbite is also more common in individuals who are rescued only after many hours due to unwitnessed accidents or challenging conditions (e.g. poor weather, remote location). In the prehospital setting, the focus is primarily on identifying at-risk body parts and preventing further cold exposure. Due to its relative rarity in our regions, there is usually little experience in the individual management of these patients (Ströhle et al. 2018). Affected individuals should therefore be transported to an appropriate hospital and treated with expert consultation (Gruber et al. 2023; Regli et al. 2023; Sheridan et al. 2022).

31.4.2 Negative Pressure Pulmonary Oedema

Negative pressure pulmonary oedema (NPPE) represents another potentially life-threatening complication of critical burial during the course of an avalanche accident. Since 1981, four cases of pulmonary oedema following avalanche burial lasting 5–127 min, with both open and obstructed airways, have been documented (Glisenti et al. 2016). The pathogenesis of pulmonary oedema after avalanche burial is not fully understood. It is assumed that forceful inhalation against the diffusion resistance of the surrounding snow during critical burial, and the resulting negative pressure, are causative factors. Patients often require non-invasive ventilation in hospital, and NPPE usually improves within 24 h (Pasquier et al. 2023). NPPE is a diagnosis of exclusion when there is no evidence of aspiration or pulmonary contusion.

31.4.3 Post-traumatic Stress Disorder

It is not only immediate survival and possible physical injuries which influence the long-term outcome of an avalanche accident. Recent studies show that mental health problems can also be significant consequences of an avalanche incident. In situations often accompanied by fear of death during the avalanche event, approximately 10% of survivors subsequently develop post-traumatic stress disorder (PTSD) (Leonard et al. 2021). Witnesses of injuries or fatalities in avalanche accidents, as well as professional rescuers, may also suffer from PTSD (Haraldsdóttir et al. 2014). To address this issue, it is essential first to recognise psychological distress in those affected as a serious problem, thereby enabling early detection of symptoms and prevention. Regular contact in the form of professional support and counselling should be offered generously in the weeks and months following the event. In the emergency services, peer groups among staff, consisting of individuals with similar professional experience and qualifications, can facilitate the exchange of coping strategies after stressful incidents and, if necessary, provide access to professional psychological support.

31.5 Diagnostics/On-Site Treatment

31.5.1 Risk Assessment and General Considerations for Prognosis

Ensuring the safety of rescuers is the first and most important priority in any rescue operation. Both the rescue team and the responsible incident commander must always be aware of existing and potential hazards before and during every operation, such as those arising from deteriorating snow or weather conditions or approaching darkness. This risk assessment requires not only sound knowledge and experience in evaluating local avalanche danger, but also a careful balancing of the expected risk to rescuers against the likelihood of a successful rescue of the buried persons. The anticipated survival probability of buried persons, depending on burial duration, should be factored into the decision as to whether and for how long a rescue operation should be continued.

Every ground or air rescuer entering avalanche terrain must be equipped with an avalanche transceiver and ideally with an avalanche airbag and/or an AAPD (Artificial Air Pocket Device) (Wik et al. 2022).

> The safety of rescuers takes absolute priority. The initiation and duration of an avalanche rescue operation must be adapted to the prevailing risk. In the event of significant danger, the rescue operation must be critically reviewed and, if necessary, suspended and resumed at a later time.

31.5.2 Location and Rescue on the Avalanche Debris

Due to the extremely time-critical risk of asphyxia, the survival of avalanche victims depends largely on immediate rescue. The highly time-dependent survival rate underscores the importance of immediate rescue by unburied companions (Mair et al. 2013). The probability of survival can be four times higher if the victim is rescued by uninjured companions than by an organised rescue team, as unburied companions can ideally locate and extricate the avalanche victim in less than 15 min (Mair et al. 2013). Organised rescue teams generally only reach the avalanche site after 15–30 min. Thus, avalanche victims rely on rapid companion rescue to achieve the highest possible survival rate. In Germany, Italy, Austria, and Switzerland, as well as in several other European countries, terrestrial search and rescue services with search dogs and emergency medical helicopters are on-call for avalanche rescue. Nevertheless, even under optimal conditions, it takes several minutes—usually well over 15 min—before the buried person is extricated. In summary, the survival rate of critically buried avalanche victims is approximately 80% if the victim is rapidly located, extricated, and rescued by companions, compared to less than 20% if rescued by emergency helicopter crews and mountain rescue services (Mair et al. 2013).

For companion rescue, the following applies. Upon arrival at the accident site, it takes at least 3 to 5 min to locate a completely buried person. As asphyxia is the most common cause of death in the early phase of burial, basic life support by first responders must include ventilation and chest compressions; chest compressions alone are not recommended (Brugger et al. 2013). Organised rescue differs from companion rescue, as the response time to reach the avalanche debris is longer and more equipment and personnel resources are available. If conditions permit, air rescue by emergency medical helicopters should be prioritised over ground rescue teams, as emergency medical helicopters are faster, safer and more efficient in avalanche rescue operations. However, air rescue missions may be limited by adverse weather conditions, such as poor visibility and wind, and at night. Professional medical personnel should be present on-site to treat snow-buried persons during and after rescue.

For both first responders and professional rescue teams, self-protection is the highest priority. If the risk to rescuers outweighs the potential benefit to the buried persons, rescue and on-site medical care may need to be withheld (Brugger et al. 2013; Lott et al. 2021; Van Tilburg et al. 2017). Medical equipment should be protected from cold and other adverse weather conditions. Electronic devices should be equipped with fully charged batteries or accumulators, as battery life is reduced in cold weather. Rescue equipment includes bivouac sacks, insulating layers such as blankets and aluminium blankets, chemical heat packs, a thermometer suitable for measuring core temperature, a patient monitor with defibrillator, and an airway management equipment.

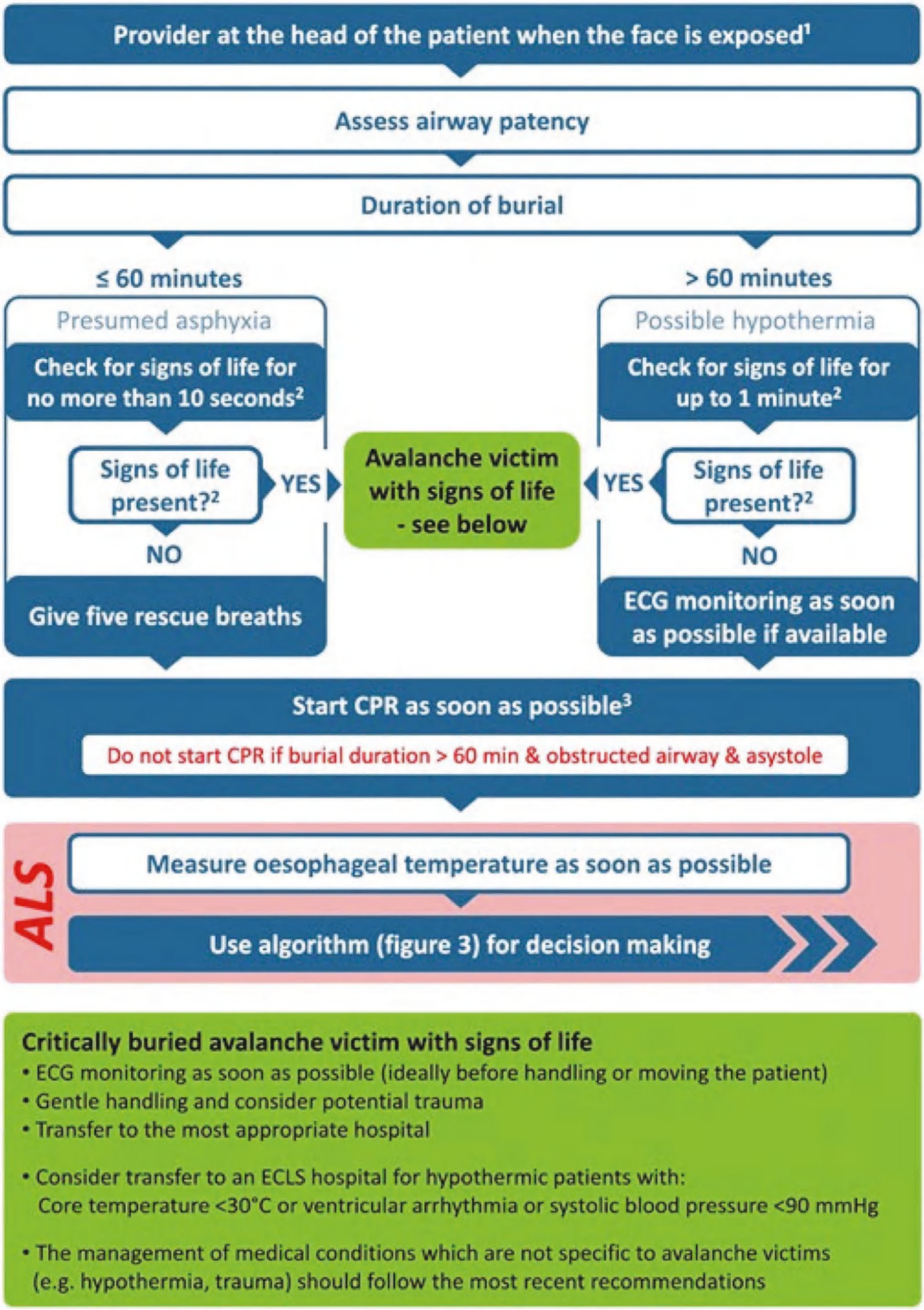
In addition to providing initial medical care, professional rescue personnel (usually emergency medical helicopter crews) are also responsible for technical and logistical rescue tasks at the avalanche site. They also make triage decisions regarding the termination of CPR, the transport of victims to a centre with extracorporeal life support (ECLS), or to other peripheral hospitals, based on the clinical condition of the victim (Lugnet et al. 2023; Schon et al. 2020; Swol et al. 2022).

31.5.3 Diagnostics and Therapy

In professional avalanche rescue operations, the principle is that rescue and initial assessment must be carried out as cautiously as possible, rather than as quickly as possible, since the critical time window of the first 60 min has usually already elapsed by the time of arrival. Rescuers should first assess the position of the victim and then gain access to the victim's head. In victims with a burial time of ≤60 min and no vital signs, asphyxia should be assumed and emergency ventilation should be initiated as soon as possible, regardless of airway patency (◘ Fig. 31.2). If the burial time exceeds 60 min, attention should be paid to airway patency or obstruction. This is followed by assessment of a potential air pocket, i.e. whether there is a free space in front of the mouth and nose. This assessment is crucial for decisions regarding resuscitation and transport and should ideally be performed by an emergency physician. If the victim's position allows, the initial assessment of the airway and vital signs should be performed before complete extrication (Rauch et al. 2021). In addition, an ECG should be applied as soon as possible (ideally using defibrillation electrodes as soon as the thorax is accessible and preferably before the victim is moved), as the detection of cardiac arrhythmias, which may be triggered by movement of the patient, is of utmost importance (Strapazzon et al. 2012).

Furthermore, core body temperature must be measured, either using an epitympanic thermometer in non-intubated patients or an oesophageal temperature probe in intubated patients (Strapazzon et al. 2014). An oesophageal probe placed with the distal end in the lower third of the oesophagus is considered the gold standard for intubated patients or those in cardiac arrest (Pasquier et al. 2020) (◘ Fig. 31.3). Epitympanic measurement with a thermistor is a reliable alternative in conscious and spontaneously breathing patients but may display falsely low temperatures in very cold environments (Strapazzon et al. 2015). Epitympanic probes that are not designed for outdoor use at low temperatures, e.g. < −20 °C, or for measuring low body temperatures, e.g. <28 °C, should not be used (Strapazzon et al. 2014). If no thermometer is available, the Revised Swiss staging system should be used (◘ Fig. 31.4). The rationale is that the level of consciousness correlates best amongst all the vital parameters with the risk of hypothermia-induced cardiac arrest (Musi et al. 2021). However, asphyxia, intoxication, or traumatic brain injury preclude the use of the modified Swiss staging system.

Pulse oximetry is not mandatory, as it may be unusable or inaccurate in cold exposure due to peripheral vasoconstriction (Rauch et al. 2021). Once the avalanche victim has been extricated, an initial assessment of vital signs and obvious injuries (trauma check) should be performed. Cardiac rhythm and core temperature should be continuously monitored throughout the rescue to detect life-threatening drops in body temperature ('after-drop') or cardiac arrest during extrication ('rescue collapse') at an early stage (Rauch et al. 2021). Ideally, during this evaluation and monitoring, defibrillator pads should also be applied, and the avalanche victim should be protected from further cooling after rescue from the snow (Brugger et al. 2013).


Provider at the head of the patient when the face is exposed¹
Assess airway patency
Duration of burial
≤ 60 minutes
> 60 minutes
Presumed asphyxia
Check for signs of life for no more than 10 seconds²
Signs of life present?²
YES
NO
Give five rescue breaths
Avalanche victim with signs of life - see below
Possible hypothermia
Check for signs of life for up to 1 minute²
YES
Signs of life present?²
NO
ECG monitoring as soon as possible if available
Start CPR as soon as possible³
Do not start CPR if burial duration > 60 min & obstructed airway & asystole
ALS
Measure oesophageal temperature as soon as possible
Use algorithm (figure 3) for decision making

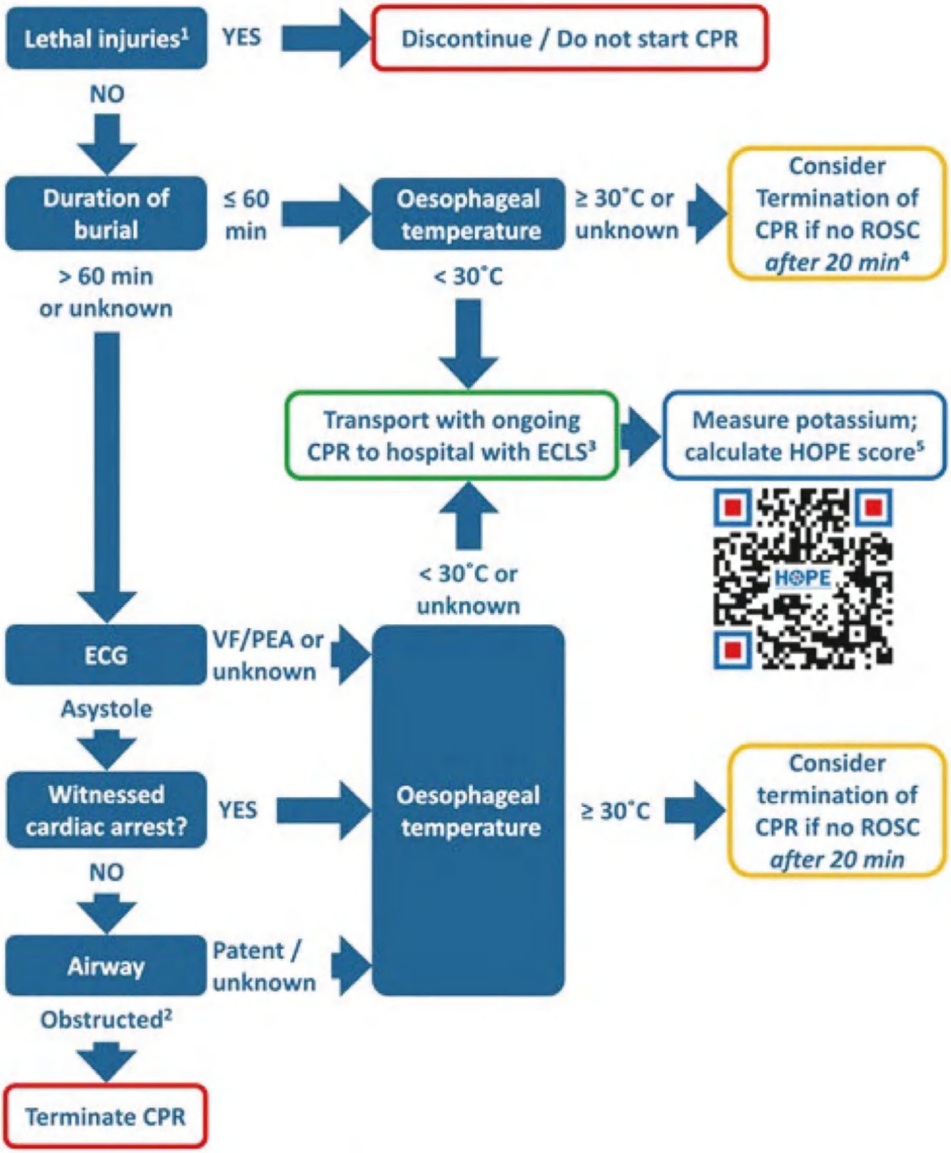
Critically buried avalanche victim with signs of life

- ECG monitoring as soon as possible (ideally before handling or moving the patient)
- Gentle handling and consider potential trauma
- Transfer to the most appropriate hospital

- Consider transfer to an ECLS hospital for hypothermic patients with:
  Core temperature <30°C or ventricular arrhythmia or systolic blood pressure <90 mmHg

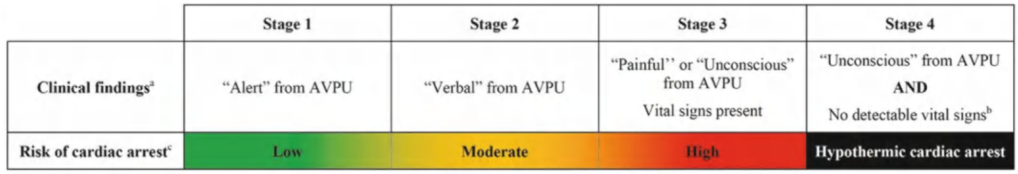
- The management of medical conditions which are not specific to avalanche victims (e.g. hypothermia, trauma) should follow the most recent recommendations

Fig. 31.2 Initial management of a critically buried avalanche victim. (Pasquier et al. 2023). *ALS* Advanced Life Support; *CPR* cardiopulmonary resuscitation; *ECLS* extracorporeal life support; *VF* ventricular fibrillation; *PEA* pulseless electrical activity


Lethal injuries¹
YES
Discontinue / Do not start CPR
NO
Duration of burial
≤ 60 min
Oesophageal temperature
≥ 30˚C or unknown
Consider Termination of CPR if no ROSC after 20 min⁴
> 60 min or unknown
< 30˚C
Transport with ongoing CPR to hospital with ECLS³
Measure potassium; calculate HOPE score⁵
HOPE
< 30˚C or unknown
ECG
VF/PEA or unknown
Asystole
Witnessed cardiac arrest?
YES
Oesophageal temperature
≥ 30˚C
Consider termination of CPR if no ROSC after 20 min
NO
Airway
Patent / unknown
Obstructed²
Terminate CPR

1. Decapitation, truncal transection, whole body decomposed
2. An obstructed or blocked airway requires that both the nose and mouth be completely filled with compact snow or debris.
3. With a deeply hypothermic patient (<28°C), if rescue is too dangerous consider delayed CPR and if transport is difficult consider intermittent CPR.
4. If core temperature measurement is not available, hypothermic CA may be considered, at the rescuer's discretion, despite a burial duration of ≤60 minutes in a victim with a patent airway and no vital signs when there is a possibility of very rapid cooling (e.g burial during ascent, low body mass index or small persons, minimally dressed, sweating before burial).
5. In-hospital prognostication of successful rewarming in an avalanche victim should include estimation of the survival probability using the HOPE score. If any doubt exists whether the avalanche victim may have asphyxiated despite critical burial, the HOPE score should be calculated using the NON-ASPHYXIA option. This will reduce the risk of under-treatment. If the HOPE score cannot be determined, the combination of a potassium <7 mmol/L and a temperature <30°C may be used instead to help indicate ECLS rewarming.

▪ **Fig. 31.3** Decision algorithm for the advanced management of critically buried avalanche victims in cardiac arrest. *ALS* Advanced Life Support; *CPR* cardiopulmonary resuscitation; *ECLS* extracorporeal life support; *VF* ventricular fibrillation; *PEA* pulseless electrical activity; *ROSC* return of spontaneous circulation



	Stage 1	Stage 2	Stage 3	Stage 4
Clinical findings[a]	"Alert" from AVPU	"Verbal" from AVPU	"Painful" or "Unconscious" from AVPU Vital signs present	"Unconscious" from AVPU AND No detectable vital signs[b]
Risk of cardiac arrest[c]	Low	Moderate	High	Hypothermic cardiac arrest

Fig. 31.4 Revised Swiss staging system for the classification of accidental hypothermia. (Adapted from Musi et al. 2021)

[a] In the revised Swiss staging system for the classification of accidental hypothermia, 'alert' corresponds to a GCS score of 15; 'voice' to a GCS score of 9–14, including confused patients; 'pain' and 'unconscious' correspond to a GCS score <9. Although shivering is not used as a staging criterion in the modified Swiss staging system, its presence generally indicates a temperature >30 °C, a temperature at which hypothermic cardiac arrest is unlikely (Pasquier et al. 2018).

[b] Check for signs of life (pulse and especially breathing) for up to 1 min (Lott et al. 2021).

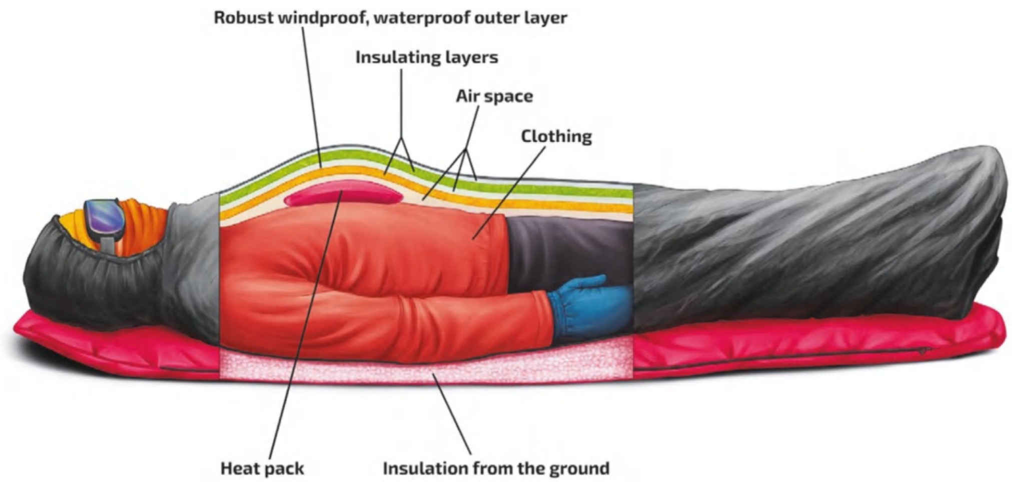
[c] The colour transition between stages indicates the overlap of patients within the groups. The estimated risk of cardiac arrest is based on accidental hypothermia as the sole cause of the clinical findings. If other conditions impair consciousness, such as asphyxia, intoxication or trauma, the modified Swiss staging system may falsely predict a higher risk of cardiac arrest due to hypothermia. Caution is advised if a patient remains in the 'alert' or 'voice' stage but shows signs of haemodynamic or respiratory instability, such as bradycardia, bradypnoea or hypotension, as this may indicate progression to a stage with a higher risk of cardiac arrest.

31.5.4 Trauma Management

Current resuscitation guidelines emphasise gentle extrication and the application of spinal immobilisation measures in all avalanche victims (Lott et al. 2021; Van Tilburg et al. 2017). General principles of trauma management also apply to avalanche victims: The current guidelines emphasise early haemorrhage control (possibly with a tourniquet), initial management according to the 'damage control' concept, airway management, stabilisation of life-threatening injuries and immediate evacuation for definitive care (Spahn et al. 2019; Sumann et al. 2020). Spinal immobilisation, splinting of limb fractures and adequate analgesia should be provided during on-site management and transport. In cases of severe traumatic brain injury, e.g. GCS <9, early endotracheal intubation and normocapnic ventilation are recommended; adequate cerebral perfusion pressure should also be maintained by keeping systolic blood pressure ≥110 mmHg or mean arterial pressure ≥80 mmHg (Picetti et al. 2023; Rossaint et al. 2023). Polytrauma with accidental hypothermia can rapidly lead to a life-threatening deterioration due to the vicious cycle of bleeding → acidosis → hypothermia → bleeding (Rauch et al. 2021). For this reason, avalanche victims with trauma should receive immediate multilayer whole-body insulation with heat packs on the torso after extrication to limit further cooling. Rapid transport to a trauma centre is essential. Survival rates in victims of traumatic cardiac arrest are low; prolonged CPR is associated with poor neurological outcome (Rauch et al. 2021).

31.5.5 Hypothermia Management

In all unconscious avalanche victims who have not died from asphyxia within the first 35 min after burial, the presence of hypothermia should be assumed, especially if burial time exceeds 60 min (Boyd et al. 2010). Rescue should be performed gently, with minimal movement and with immobilisation, to avoid 'rescue collapse', i.e. hypothermia-induced cardiac arrest during extrication. If the victim is neither shivering nor moving, exposure to cold and wind after extrication can lead to very rapid cooling. This also increases the risk of fatal


Robust windproof, waterproof outer layer
Insulating layers
Air space
Clothing
Heat pack
Insulation from the ground

■ **Fig. 31.5** Multi-layer insulation of an avalanche victim. (From Paal et al. 2022b)

cold-induced arrhythmia, most commonly ventricular fibrillation or asystole (Musi et al. 2021). All immobilised avalanche victims must be insulated throughout prehospital care, and external heat should be applied immediately after extrication from the snow. Removing wet clothing increases the victim's comfort, but in a cold or windy environment, it leads to rapid cooling and is not necessary if the victim can be sealed in multi-layer insulation (■ Fig. 31.5) (Van Tilburg et al. 2017).

If an avalanche victim is unconscious during rescue, core temperature should be closely monitored to distinguish between severe hypothermia and other causes of unconsciousness, such as traumatic brain injury (Rauch et al. 2021). Severely hypothermic avalanche victims with a core temperature <30 °C, systolic blood pressure <90 mmHg, a heart rate <45 bpm, ventricular arrhythmia or other cardiac instability should be transported directly to a centre offering ECLS as a rewarming option (■ Figs. 31.2 and 31.3) (Lott et al. 2021; Rauch et al. 2021).

31.6 Transport and In-Hospital Therapy

Transport of an avalanche victim should be organised urgently due to the potential for rapid clinical deterioration. When selecting the destination hospital, avalanche-associated injuries and body core temperature should be taken into account (■ Figs. 31.2 and 31.3).

Before transporting patients in therapy-refractory cardiac arrest, the critical question of benefit must be addressed. Transport of avalanche victims undergoing ongoing CPR without a chance of survival should be avoided, e.g. in cases of burial exceeding 60 min, obstructed airway and asystole on discovery (Pasquier et al. 2023). The European Resuscitation Council (ERC) has established criteria for triage and transport decisions by rescuers trained in advanced life support (ALS) at the scene (Lott et al. 2025. In particular, based on epidemiological and experimental studies, the duration of burial, initial core temperature and serum potassium levels for avalanche victims in cardiac arrest have been revised and modified to avoid futile primary and secondary transports (Lott et al. 2021; Pasquier et al. 2018, 2019).

Treatment of avalanche victims should follow the algorithm of the International Commission for Alpine Rescue Medical Commission (ICAR MedCom) (Pasquier et al. 2023). In principle, it should be noted that in cases of cardiac arrest after a burial duration of ≤60 min (or a core temperature ≥30 °C), hypothermia as the cause is highly unlikely. In such cases, the ERC 2021 guidelines for the management of normothermic cardiac arrest apply, and resuscitation efforts may be discontinued after 20 min of unsuccessful CPR without ROSC; in these cases, the patient has died not from hypothermia but from trauma or asphyxia. Hypothermic cardiac arrest may, at the discretion of the rescuer, be considered even after a short burial duration of ≤60 min in a victim with a patent airway and no vital signs, if there is a possibility of very rapid cooling, e.g. due to inadequate clothing, slim body habitus, a cold and windy environment or burial following physical exertion.

However, if the duration of burial is >60 min (or the core temperature is <30 °C) and the avalanche victim is found in cardiac arrest with a patent airway, transport with ongoing CPR should be undertaken to a hospital capable of ECLS rewarming. If direct transport to an ECLS centre is not feasible within a reasonable timeframe, e.g. within 6 h, non-ECLS rewarming should be performed at the most suitable hospital (Paal et al. 2016). Triage should be based on the HOPE score ('hypothermia outcome prediction after extracorporeal life support for hypothermic cardiac arrest patients'; ► https://www.hypothermiascore.org), which is based on six parameters and not solely on serum potassium levels (Pasquier et al. 2018, 2019). If calculation of the HOPE score is not possible, a potassium level >7 mmol/l at a core temperature <30 °C may be considered a criterion for terminating CPR (Lott et al. 2021). The HOPE score is the recommended prognostic tool for patients in cardiac arrest with a core temperature <30 °C. In critically buried avalanche victims, asphyxia should be entered as the cause of cardiac arrest in the HOPE score. Hypothermia should be considered the most likely cause of cardiac arrest if it is observed after extrication and the burial time exceeds 60 min. In this case, the HOPE score should be calculated using the non-asphyxia scenario. Some authors have questioned the value of the HOPE score for triage and prognostic assessment in avalanche victims, but no better tool is currently available (Wallner et al. 2022). Larger case numbers are needed to refine the HOPE score for avalanche victims; currently, there are fewer than ten survivors of cardiac arrest after avalanche burial who have been rewarmed using ECLS (Paal et al. 2022a).

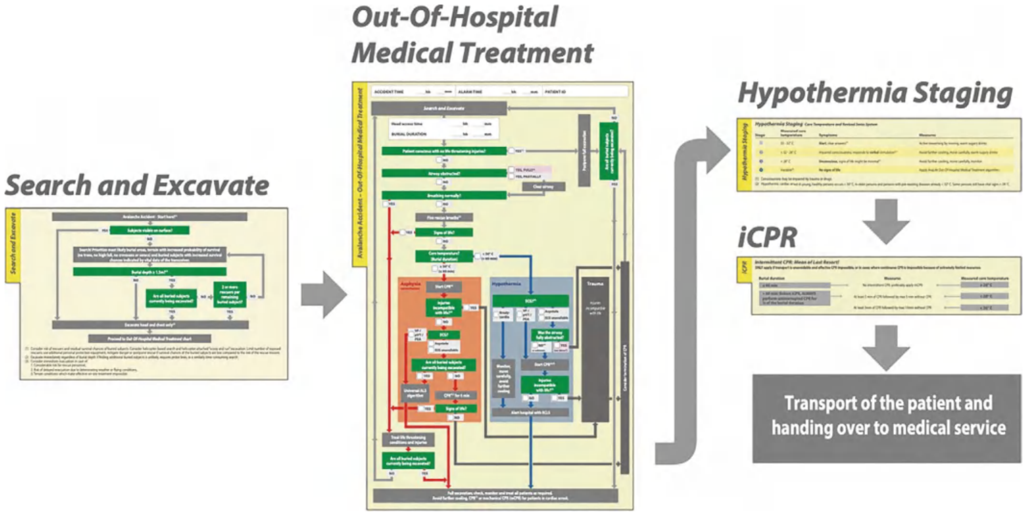
All avalanche victims with cardiovascular instability (i.e. ventricular arrhythmias or systolic blood pressure <90 mmHg) and a core temperature <30 °C should be transported to an ECLS centre (Lott et al. 2021). There, rewarming should be performed using non-invasive and externally active methods, i.e. forced air warming and warmed infusions. If the patient suffers hypothermia-induced cardiac arrest, rewarming should be performed with ECLS, ideally using extracorporeal membrane oxygenation (ECMO). ICAR MedCom has summarised the key recommendations for action in avalanche accidents and assigned levels of evidence and recommendations.

31.7 Multiple Burial—Mass Casualty Incidents Involving Avalanche Victims

In avalanche accidents, multiple persons may be buried. In more than 10% of avalanche rescue helicopter missions in Austria, for example, more than four victims are reported (Mair et al. 2013). ICAR MedCom issued recommendations for on-site management in such cases several years ago (Blancher et al. 2018). If sufficient resources are not available, the guidelines recommend prioritisation. Rescue should take the highest priority, and medical care should focus on victims with present vital signs and a burial time of less than 35 min. In avalanche victims with cardiac arrest and a burial time between 35 and 60 min, CPR should not be initiated. If the burial time exceeds 60 min, CPR should only be started if the airway is clear (Blancher et al. 2018).

31.8 AvaLife

To provide a decision-making aid in the time-critical situation of multiple burials with limited rescuer resources, for example, four buried victims and two rescuers on site, AvaLife was developed based on mathematical modelling using Monte Carlo simulation. AvaLife differs from other algorithms in that it is not only a medical care and CPR algorithm (Genswein et al. 2022). AvaLife offers a systematic, flowchart-based approach for technical search and rescue as well as prehospital medical management of avalanche victims. With its four different modules in the Basic Life Support (BLS) version, it is a comprehensive decision-making tool that can also be used as a protocol for recording key patient data for further hospital treatment (■ Fig. 31.6). A central aspect of AvaLife is that, in the case of a shortage of rescuers and remaining buried persons, resuscitation of a victim in cardiac arrest should only be performed for 6 min. Afterwards, attention should be given to the other buried persons, as they may still be at risk of asphyxiation. The rationale is to achieve the greatest benefit for the largest number of people when resources are limited. AvaLife can be used in avalanche scenarios involving both single and multiple burials. In addition, the algorithm can serve as a memory aid on site and as an avalanche checklist for recording medically relevant data, such as burial time and airway status, for ongoing in-hospital care (Genswein et al. 2022).


Out-Of-Hospital Medical Treatment
Search and Excavate
Hypothermia Staging
iCPR
Transport of the patient and handing over to medical service

■ **Fig. 31.6** Multi-module AvaLife algorithm for single and multiple burial with limited resources, including recommendations for search, extrication, medical management and transport decision to hospital. (Genswein et al. 2022)

31.9 Prognosis and Decision-Making Including Organ Donation Decision in Brain Death

31.9.1 Individual Prognosis

The central question in establishing an individual prognosis is the temporal relationship between hypothermia and asphyxia. If asphyxia occurs before hypothermia, the prognosis is significantly worse. When using the HOPE score, the option 'hypothermia without asphyxia' can only be selected in cases where an association of cardiac arrest with asphyxia can be excluded (Rauch et al. 2021). However, robust data on its prognostic sensitivity and specificity in hypothermic avalanche victims are scarce, so treatment decisions for avalanche victims should be supported by the HOPE score but not based solely on the result of this calculation (Wallner et al. 2022). The less reliable but simpler prognostic method using threshold values for serum potassium (7 mmol/l) and core body temperature (30 °C) can be used as an alternative if the HOPE score cannot be calculated, although its prognostic value is lower (Brugger et al. 2019). As in many borderline cases in medicine, a balanced interdisciplinary assessment is required in these situations. In cases of doubt or conflicting findings, additional parameters should be considered, such as possible cooling after extrication, polytrauma, and laboratory parameters including pH, serum lactate and coagulation parameters.

31.9.2 Organ Donation Decision

Despite guideline-based treatment and decision-making, more accurate survival predictions, and improved treatment methods, there are still patients who, after a critical burial, initially survive but are later declared brain dead during their hospital stay due to asphyxia or severe traumatic brain injury (TBI). However, due to usually rapid rescue and therapy, severe hypoxia-related damage to other organs in these mostly young, healthy patients can often be avoided. Retrospective data show that organ transplantation from avalanche victims can be successfully performed (Gasteiger et al). This makes these patients potential donors of life-saving organs, provided that the legal and ethical requirements are met and, ideally, the patient's wishes permit it. Against this background, patients should not be denied a trial of extracorporeal membrane oxygenation from the outset, even in cases of presumably poor prognosis (such as a low HOPE score). The possibility of organ donation in this patient group should in any case be considered, also to address the problem of organ shortage (Rauch et al. 2023).

31.10 Summary

At least 90% of avalanches involving injuries or fatalities are triggered by recreational sports enthusiasts and are dry slab avalanches. The prevention of avalanche accidents encompasses several levels. These include avoiding avalanche involvement, preventing burial through avalanche airbags, and delaying asphyxia after burial by means of AAPD. The mortality rate of critically buried avalanche victims is approximately 50%. The most common cause of death is asphyxia, followed by trauma, while hypothermia is a rare cause of cardiac arrest. However, severe hypothermia has a neuroprotective effect, resulting in a favourable prognosis for hypothermic cardiac arrest. An avalanche victim who suffers a witnessed cardiac arrest after extrication has a good chance of survival with a favourable neurological outcome. Clear differentiation between asphyxial and hypothermic cardiac arrest enables not only optimised triage but also optimised resource management. The initial management of avalanche victims in cardiac arrest after a short (60 min) burial should focus on ventilation. Management of cardiac arrest after prolonged (>60 min) burial includes extended assessment of signs of life (1 min) and vital parameters, as well as the diagnosis of hypothermia. Avalanche victims with a burial duration >60 min, obstructed airways, and asystole should not be resuscitated. Those with a core temperature <30 °C, as well as those with unknown core temperature but prolonged (>60 min) burial and witnessed cardiac arrest or a cardiac rhythm such as ventricular fibrillation or pulseless electrical activity, should be transported under ongoing CPR to a hospital with ECLS capabilities.

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Canyoning and Caving Accidents

Inigo Soteras and Giacomo Strapazzon

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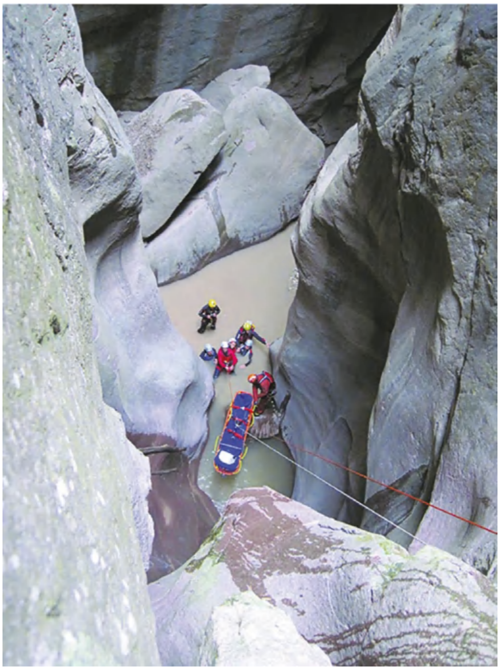
Canyoning and caving are adventure and outdoor sports closely associated with rock and water. Canyons and caves are found worldwide—in mountains, tropical rainforests, alpine and arctic glaciers and even in historic cities such as Naples and Rome. Canyons are formed by chemical and physical interactions between rock and water over millions of years, which is why they are found in such diverse geological formations such as basalt, granite, limestone, lava and even ice. Water plays a predominant role, and water levels can vary considerably depending on the season and amount of precipitation. Canyons and caves may be completely filled with water or entirely dry (so-called dead caves). The force of water creates a wide variety of formations such as pools, waterfalls, shafts and siphons, as well as crater-like structures, fissures, mud pools and springs. These natural phenomena make these sports particularly attractive.

Above all, canyoning has become a very popular recreational activity due to its spectacular environment and contact with water. Anyone in good health can explore canyons and caves without expensive equipment. However, complete isolation from the outside world, darkness and extreme weather conditions can be challenging for some, and the mental, physical and physiological demands of these activities are often underestimated (Zuccarelli et al. 2019). Potential hazards include obstacles in the water, cold or heat, differences in altitude, narrow passages and dangerously slippery surfaces (Strapazzon and Larsen 2017).

Engaging in canyoning or caving activities without local knowledge and experience is extremely risky and often leads to catastrophic accidents (◘ Fig. 32.1). The most serious accident to date occurred in 1999 in the Saxetbach Gorge (Switzerland), where 21 people drowned due to a sudden surge of water (Strapazzon and Larsen 2017), resulting in an exceptionally complex search and rescue operation (Schneider et al. 2016; Van Waart et al. 2020).



◘ **Fig. 32.1** Canyon rescue operation. (Image credit: Erwin Kob, reproduced with kind permission)

> The force of water has shaped canyons and caves, and water also represents the greatest hazard for adventurers and rescue teams.

32.1 Specific Hazards

32.1.1 Canyoning

Canyons are usually traversed in the direction of the water flow. There is often no escape route between the entry and exit points, so once inside the canyon, one must follow it to the exit or confluence. Canyoning requires a range of skills, such as downclimbing, abseiling, swimming, diving, jumping into water from heights of up to 10 m, setting intermediate anchors and fixed points, crawling, and hiking (Stephanides and Vohra 2007; SNATE 2013; Strapazzon and Larsen 2017). The ground can be extremely slippery when wet or dry, and falls due to simple slips are common. Every participant should be aware of the specific risks associated with the planned route, particularly vertical sections and narrow passages with fast flowing water. Before commencing a canyoning tour, it is essential to be familiar with the topography in order to bring the appropriate equipment in sufficient quantity. For example, the maximum height of the abseil points must be known to ensure the rope is long enough. It is also necessary to know the catchment area of the watercourse to estimate the expected water volume in case of sudden rainfall or snowmelt. Therefore, knowledge of the weather forecast is also crucial when planning the tour. Equipment required is presented in ◘ Table 32.1.

Before abseiling down a waterfall, the rope should be laid out so it can be easily thrown and does not become tangled; otherwise, there is a risk of becoming trapped in the waterfall and drowning. The ropes must be completely intact and used in such a way that they are not damaged by sharp edges.

The ends of the rope should always remain visible and accessible outside the water, and unlike in climbing, no knot should be tied at the end so as to avoid

◘ **Table 32.1** Equipment for canyoning and caving

Canyoning	**Caving**
Canyoning harness	Caving harness (combined chest and sit harness)
Helmet	Helmet
Accessory cords	Accessory cords
Carabiners and locking carabiners (e.g. mosquito Freino®)	Carabiners and locking carabiners (e.g. Maillon Rapide)
Descender carabiners (e.g. Pirana®, Oka®)	Descender carabiners (e.g. stop®, simple®)
Ascending carabiners and pulleys for hauling systems (e.g. duck®, micro Traxion®)	Ascending carabiners and pulleys for hauling systems (e.g. handled, Croll®, Pantin®)
Canyoning and static ropes	Static ropes
Equipment for fixed anchors (e.g. anchors, chains)	Equipment for fixed anchors (e.g. anchors, chains)
Rope bags	Rope bags
Rope protectors	Rope protectors
Dry containers	Special clothing (e.g. Cordura®)
Canyoning clothing (including neoprene gloves and socks)	Gloves
Canyoning shoes	Shoes with rubber soles
Headlamp	Headlamp (e.g. LED)
First aid kit	First aid kit
Knife or scissors	Knee pads
Whistle	
Diving goggles	

entrapment. The section of the watercourse ahead should be explored before entering the water, as dangerous water turbulence, such as breaking waves, hydraulic jumps, siphons and undercuts, can be fatal (SNATE 2013; Strapazzon and Larsen 2017). It is often better to look for an exit underwater rather than to remain at the water's surface in order to escape such currents. Submerged rocks and driftwood can cause injuries and may also result in entrapment and drowning (SNATE 2013; Strapazzon and Larsen 2017).

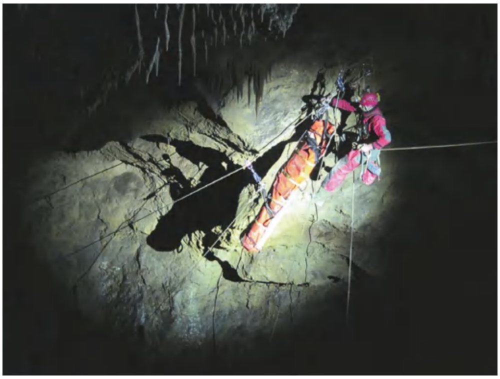
32.1.2 Caving

Caves can be so large that the far end is not visible, while in other places fissures may be too narrow to pass through. Caves may run horizontally or drop vertically. The ground is usually muddy and slippery, and it is completely dark. Unlike canyons, caves often resemble an underground labyrinth with numerous main and side passages and no exit (Soteras et al. 2021).

Safety and the prevention of even the smallest accident are of utmost importance, as rescue operations can be technically very challenging and time-consuming, and outcomes can be poor even when injuries are minor. Recent examples of the extreme difficulty of cave rescues include incidents in the Riesending cave in Germany and in a cave in Thailand. In the former, it took almost 12 days to bring the injured speleologist to the surface, due to the high technical complexity of the cave and the equipment required to transport the patient and ensure rescuer safety. The rescue involved 7 doctors and more than 200 rescuers working inside the cave, supported by a further 526 rescuers and around 100 h of helicopter flights, including night flights, to transport personnel and equipment (Schneider et al. 2016). In the Thai cave incident, 12 children and one adult were anaesthetised before being rescued from the flooded cave, which was more than 1 km long (Van Waart et al. 2020).

The equipment differs from that used in canyoning, particularly with regard to rope techniques (◘ Table 32.1). In caves, only static ropes are used for belaying (Strapazzon et al. 2010; Soteras et al. 2021). Rope belays, abseiling techniques, rope brakes and ascenders have in part been developed specifically for caving and cave rescue. Equipment also includes specialised light sources, protective clothing and particularly compact rucksacks for narrow passages (Soteras et al. 2021).

Caving involves exposure to extreme temperature fluctuations, and clothing should therefore be selected accordingly. In narrow cave sections with strong draughts, the wind-chill effect can lead to rapid cooling, while in other areas, temperatures may exceed 40 °C. Some caves also contain sections with hazardous concentrations of carbon dioxide, methane, hydrogen sulphide and radon. Rare pathogens such as *Histoplasma capsulatum*, *Leptospira* species, schistosomiasis, tick-borne relapsing fever, other *Borrelia* species, rabies virus and endemic mycoses can be transmitted by the subterranean fauna (Igreja 2011; Gundacker et al. 2017). An example of a cave rescue operation is shown in ◘ Fig. 32.2.



◘ **Fig. 32.2** Cave rescue operation. (Image rights: Hermann Brugger, with kind permission)

32.2 Patterns of Injury

32.2.1 Canyoning Accidents

Injuries are the most common reason for rescue operations, accounting for 75% (Boyet 2003) to 81% (Soteras et al. 2015). The extremities are most frequently affected (Rigot-Nivet 2003; Soteras et al. 2015; Ströhle et al. 2019), for example, supination injuries of the ankle joint due to misjudged jumps or slipping. Tobogganing can result in shoulder dislocation, which, because of pain, may make further progress in the canyon terrain impossible (Soteras et al. 2015; Ströhle et al. 2019). High jumps without having checked the depth of a pool (or the presence of debris) can lead to spinal injuries if the canyoner lands flat on their feet. Spinal or back injuries account for 10–16% of all canyoning-related injuries (Soteras et al. 2015; Ströhle et al. 2019).

Drowning and trauma are the leading causes of fatalities (Soteras et al. 2015; Strapazzon et al. 2018), mainly due to a lack of hazard awareness or incorrect rope techniques. Overall, the mortality rate in canyoning accidents is 3–10% (Boyet 2003; Rigot-Nivet 2003; Soteras et al. 2015; Ströhle et al. 2019; Strapazzon et al. 2018). The immense force of water is often underestimated, as a rise in water level exponentially increases both water speed and flow force (SNATE 2013). Hypothermia occurs only rarely and is likely underdiagnosed (~20%: Stephanides and Vohra 2007; 2%: Soteras et al. 2015), but sudden cooling from cold water can lead to immobilisation and drowning (Strapazzon et al. 2021). Immobility in flowing water, even when wearing a wetsuit, can result in life-threatening hypothermia after just 30 min (Strapazzon et al. 2018) (see ► Chap. 29).

Heat-related illness or dehydration occurs less frequently. Wearing a wetsuit on hot days during physical exertion outside the water can result in rhabdomyolysis, myoglobinuria and acute renal failure (Strapazzon et al. 2010, 2021). Medical conditions such as myocardial infarction, stroke or hypoglycaemia, as well as infections, snakebites, scorpion or insect stings, are less common (Boyd et al. 2007; Stephanides and Vohra 2007; Hochedez et al. 2013; Soteras et al. 2015; Strapazzon et al. 2021).

32.2.2 Cave Climbing Accidents

Similarly, in cave accidents, drowning and injuries are the most common incidents. Extremity injuries account for approximately 50% of all trauma cases, followed by traumatic brain injury at around 15% (Stella-Watts et al. 2012; Petrucci et al. 2018). These accidents are caused by falls, but can also be caused by cave-ins (Stella-Watts et al. 2012).

Accidental hypothermia is also common (Stella-Watts et al. 2012). Fatal suspension trauma (suspension syndrome) (Mortimer 2011; Rauch et al. 2023), medical and neurological issues (~5%) and gas poisoning (~5%) are less frequent (Stella-Watts et al. 2012). Prolonged physical exertion, contusions, and muscle compression from the climbing harness can lead to rhabdomyolysis and renal failure (Stenner et al. 2006), and infectious diseases may occur in tropical and subtropical caves (Igreja 2011). Overall, the mortality rate for cave accidents is approximately 6% (Guidi and Pavanello 2003; Stella-Watts et al. 2012). The most common causes of death are trauma (e.g. a fall by the caver) and drowning (Cowart et al. 2014; Stella et al. 2015).

> In addition to drowning, hypothermia and injuries are the greatest risks in canyoning and cave climbing.

32.3 Canyon and Cave Rescue

Since the 1980s, the number of canyon and cave rescue operations has increased in both Europe and the USA (Strapazzon et al. 2021; Soteras et al. 2021). Canyoning is among the most frequent activities leading to search and rescue missions in certain geographic regions, accounting for up to 50% of such operations (e.g. in Zion National Park, USA, or the Sierra de Guara, Spain) (Soteras et al. 2015; Beasley et al. 2016; Strapazzon et al. 2021). Overall, canyon and cave rescues represent between 0.3% and 2% of all search and mountain rescue operations (Heggie and Amundson 2009; Guidi and Pavanello 2003) but can be up to 22% (Soteras et al. 2015).

The number of search and rescue operations following canyoning accidents shows a seasonal peak, similar to other outdoor activities. The incidence of accidents increases during the spring and summer months. In contrast, search and rescue missions following caving accidents are distributed throughout the year.

Search and rescue operations for canyoning and caving accidents in Europe most often involve the rescuing of an injured patient who is unable to move independently (Soteras et al. 2015, 2021; Strapazzon et al. 2018, 2021). In the USA, however, cave search and rescue missions usually involve the recovery of cave visitors who are rarely seriously injured (Stella-Watts et al. 2012).

Extreme temperatures, water, prolonged transport times and the complete lack of communication with the outside world make rescues from canyons and caves among the most demanding, dangerous and challenging rescue operations. In 2017, IKAR MedCom published consensus guidelines for on-site management and transport of patients following canyoning accidents, providing an evidence-based guide for canyon rescue teams and medical professionals on effective rescue practices and medical management (Strapazzon et al. 2018). To date, there are no international guidelines for cave accidents to inform operational strategy or treatment. Existing recommendations for rescue organisations primarily address the technical aspects of extraction, while the specific medical issues have so far received little analysis or discussion.

32.3.1 Rescue, Risk Management and Communication

In canyoning and caving accidents, alerting emergency services can be delayed by many hours, as direct contact with the outside world is often not possible (Boyd et al. 2007). The ICAR MedCom guidelines emphasise that specific risk assessment and risk management are essential in rescue operations, particularly with regard to weather forecasts and water levels (Strapazzon et al. 2018). Specialised rescue techniques to avoid hazardous situations should be emphasised in training. The decision to attempt a rescue should only be made once it has been established that it is safe for rescuers to enter the emergency area and assess the situation in detail. Locating and accessing the accident site can be challenging for rescue teams. The duration of canyon rescue operations ranges from 2 h (Boyet 2003; Rigot-Nivet 2003; Soteras et al. 2015) to 12 h (Soteras et al. 2015). In cave rescues, the alarm is usually raised some hours to days after the accident, as in the case of the Riensending rescue (Stella-Watts et al. 2012; Schneider et al. 2016; Strapazzon et al. 2021).

The IKAR MedCom guidelines recommend that emergency teams operating in canyons possess specific technical skills for ground and aerial search and rescue operations to ensure safe working conditions in canyons (Strapazzon et al. 2018). The medical care during canyon search and rescue operations should be based on the available therapeutic options, with the specific treatment limitations clearly defined according to the scenario. Constraints may include the environment (which can be cold and wet), limited personnel, technical and medical resources and potentially prolonged rescue times (Strapazzon et al. 2018). The same considerations apply to search and rescue operations in caves.

In most canyon rescues, a helicopter is deployed (Soteras et al. 2015; Ströhle et al. 2019). Although helicopters can expedite rescue, for example, by winching in gorges and/or transporting the rescue team, in most cases, casualties must first be rescued and treated on the ground (Strapazzon et al. 2018, 2021; Soteras et al. 2021).

The ICAR MedCom guidelines indicate that trauma care often takes place in technically complex environments. Injuries should be managed in accordance with established guidelines. The limitations of canyon and cave rescue must be taken into account, particularly the prolonged rescue times and environmental exposure, which are challenging and influence the therapeutic options (Strapazzon et al. 2018, 2021; Soteras et al. 2021).

> During canyon or cave rescue, the entire team should be able to move safely within a canyon or cave, be aware of the hazards, master all safety techniques and be well equipped to withstand extreme environmental conditions such as cold and water.

In both canyons and caves, it is sometimes impossible to transport an injured person in a supine position. If waterfalls, rock crevices or cave passages are too narrow and steep for horizontal transport, a slanted or even vertical position of the casualty must be accepted, with all the associated haemodynamic consequences.

Special stretchers and securing techniques are required. In caves, it may be necessary to widen impassable constrictions using heavy tools. In these critical sections, transport should be coordinated by the emergency physician or an experienced paramedic, and the patient should be monitored with particular care. There are specific risks from cold, but also from toxic gases or sudden rises in water levels (Hooker and Shalit 2000).

Good communication between team members and between ground and air rescue is essential, as is the use of waterproof radios (e.g. YAESUTM VX-170) and whistles. Conventional wired telephones are still used in cave rescue, as radio communication is not possible through rock. One of the most widely used is the Through Earth Digital Radio Appliance (TEDRATM-S. 1) (Bessone et al. 2013), and more recently, digital systems such as Cave-Link have also been employed. Once a telephone line is established, it can be used not only for voice communication but also to provide Wi-Fi for the transmission of medical images (Petrucci et al. 2018). At the cave entrance, a depot should be set up for energy and food supplies, for storage of equipment and as a patient care centre.

32.3.2 Equipment

All medical equipment for canyon and cave rescue operations should be kept dry in waterproof containers. Sterile supplies must be individually sealed and regularly replaced (Strapazzon et al. 2021; Soteras et al. 2021). In canyons, only buoyant containers should be used (Strapazzon et al. 2018, 2021; Soteras et al. 2021). As with terrestrial mountain rescue, all equipment for canyon and cave rescue should be as compact and lightweight as possible, modular in design and individually adapted to the personnel's training level. The ICAR MedCom guidelines recommend that the equipment should include, among other things, modules for analgesia, materials for immobilisation and splinting and specialised modules for airway management and ventilation (Strapazzon et al. 2018).

In Italy, for example, there are three modules for cave rescue. Module 1 contains the medical equipment for the trained paramedics to secure the airway, maintain circulation and provide trauma care (Soteras et al. 2021). Apart from a pulse oximeter and an epitympanic thermometer for measuring core body temperature, the module contains no electronic devices. Module 2 includes high-energy drinks and food, as well as personal hygiene items and a heat pack. The supplementary module 'K' contains multifunctional neoprene material for splinting injured limbs and a Kendall Extrication Device. An additional module for the emergency physician contains medical equipment for airway management, ventilation, haemorrhage control and analgesia (Soteras et al. 2021).

Oxygen is generally not available, as oxygen cylinders do not provide sufficient supply for the duration of most rescues. In addition to intravenous cannulas, intraosseous needles are also available, as well as preparations for buccal or intranasal (e.g. MAD™) analgesia. Parenteral administration of analgesics can be risky during canyon or cave rescues, as continuous monitoring of the patient is not possible in technically challenging sections. Regional nerve blocks are an effective and safe alternative for complex rescue operations but are reserved for use by experienced physicians (Gros et al. 2012; Moser et al. 2023).

The ICAR MedCom guidelines recommend irrigating wounds to reduce infection rates. Systemic antibiotic prophylaxis should be administered in cases of open fractures and is advisable for severe wounds (Strapazzon et al. 2018).

32.3.3 Patient Assessment, Initial Treatment and Evacuation

The rescue team should be capable of independently assessing and providing initial treatment to casualties. Every effort should be made to bring an emergency physician or trained paramedic to the scene (Hooker and Shalit 2000). Due to the long transport times, the medical strategy for canyon and cave rescues follows the 'stay and play' principle, using minimal equipment.

Each rescue operation must be assessed individually and adapted to the technical situation; therefore, flexibility and improvisation skills are essential. The safety of the team takes absolute priority. The operations centre should be kept continually informed about the patient's condition and should organise the supply of equipment and personnel. Findings and interventions should also be documented continually (Mengelle and Durand 2003; Strapazzon et al. 2021; Soteras et al. 2021).

> In addition to regular standardised training, flexibility, communication and logistics are crucial for the success of technically demanding and prolonged rescue operations.

After the initial vital signs check, securing the airway and circulation are the highest priorities. The casualty should be undressed as little as possible to prevent hypothermia. After initial treatment (according to the ABCDE approach), the patient should be moved to a sheltered location, where the secondary, thorough examination (i.e. trauma check) is performed, and the first important measures such as splinting, immobilisation, protection from cold and administration of fluids and energy are carried out (Mengelle and Durand 2003; SNATE 2013; Strapazzon et al. 2021; Soteras et al. 2021). It has occasionally been necessary to administer blood and parenteral nutrition due to the duration of the rescue (Armstrong 2015; Schneider et al. 2016).

If prolonged transport is anticipated, analgesics, fluids and possibly antibiotics should be administered before transport starts. Also, joint dislocations and displaced fractures should be reduced and fractures splinted to prevent vascular or nerve injury. When positioning the patient on the rescue stretcher, pressure damage should be prevented by correct positioning of the limbs and padding of vulnerable areas. Only after completion of medical care—that is, when breathing and circulation are stabilised, the patient is protected from cold, and is largely pain-free and secured in the rescue stretcher—can transport begin. Clinical monitoring of vital signs should be as regular as possible.

> In addition to medical expertise, canyon and cave rescue operations require technical and topographical knowledge, psychological resilience and physical fitness.

Specialised rescue stretchers are available for transport in canyons (e.g. Kong™) and caves (e.g. Petzl™). For canyon rescues, these are waterproof and buoyant stretchers in which the head and body can be stabilised and protected from jolts, allowing safe evacuation over rock edges, waterfalls and flowing water (SNATE 2013; Strapazzon et al. 2021). Stretchers for cave rescue, on the other hand, are lightweight and compact, providing sufficient space for comfortable and pain-free positioning (Soteras et al. 2021).

The casualty is secured in the stretcher with chest and pelvic straps. The stretcher can be suspended from the rope using accessories so that its orientation can be adapted to any terrain topography, allowing the casualty to be transported safely in a horizontal, laterally inclined, oblique or vertical position. However, during complex manoeuvres (such as cableways or hauling with counterweights), it is not possible to provide continuous clinical monitoring of the casualty.

Conclusion

Safety is the highest priority in canyon and cave rescue. These operations are generally terrestrial and therefore resource- and time-intensive. In addition to specialised training and specific equipment, a precise knowledge of the topography is essential to successfully complete a rescue operation.

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Suspension Syndrome

Raimund Lechner and Simon Rauch

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The pathophysiology and management of suspension syndrome have been the subject of controversy since the 1970s. According to current knowledge, a neurocardiogenic reflex mechanism is the primary trigger. The most important preventive measures include activation of the muscle pump by moving the legs and/or standing up in foot loops or pushing off nearby structures. Treatment follows the cABCDE algorithm. In the event of resuscitation, the most likely reversible causes are hyperkalaemia, pulmonary embolism, hypothermia and hypoxia due to airway obstruction resulting from the suspended position.

33.1 Definition, Epidemiology and History

The term ‘suspension trauma’ is misleading in this context, as the patient does not necessarily have to sustain an injury. In line with international literature, the term ‘suspension syndrome’ should be used instead (Rauch et al. 2023). Similarly, terms containing ‘harness’, such as ‘harness syncope’ or ‘harness syndrome’, should be avoided, as the syndrome can also occur during suspension without a harness (Rauch et al. 2023).

> *Suspension syndrome is a circulatory depression with potentially fatal outcome caused by immobile, nearly vertical, free suspension.*

Precise data on the incidence of suspension syndrome are not yet available; overall, clinically relevant cases appear to be extremely rare. For example, a survey among industrial climbers reported no cases in 5.8 million rope-secured working hours (Seddon 2002). However, numerous case reports exist in which mountaineers and cavers have suffered suspension syndrome and, in some cases, died without significant other injuries (Mortimer 2011). In experimental studies, subjects suspended motionless in a harness reported severe malaise and, in some cases, syncope (Lanfranconi et al. 2017, 2019; Rauch et al. 2019; Orzech et al. 1987; Madsen et al. 1998). However, the incidence and mortality, as measured by published case reports, appear to have declined in recent decades, which is attributed to increased awareness of the syndrome, occupational safety regulations, rescue techniques including self-rescue, and modern harness systems.

To better distinguish between the various manifestations of suspension syndrome and to standardise future studies and case reports, the following classification has been developed. There should be no other injuries or illnesses which may be responsible for the symptoms (e.g. hypoglycaemia, hypothermia) (Rauch et al. 2023).

- **Acute Suspension Syndrome**
  - Presyncope (e.g. dizziness, confusion, pallor, cold sweating, visual disturbances, nausea, bradycardia),
  - Syncope,
  - Cardiac arrest during suspension,
  - Cardiac arrest within 60 min after rescue from the suspended position.

- **Subacute Suspension Syndrome**
  - Sensorimotor deficit in the legs lasting more than 24 h,
  - End-organ dysfunction, particularly rhabdomyolysis-associated acute renal failure,
  - Cardiac arrest at least 60 min after rescue from the suspended position.

The pathophysiology and management of suspension syndrome have been the subject of controversial discussion since the 1970s (Flora and Hölzl 1972). In a systematic review, only 23 studies with objectifiable patient and study participant data were identified, compared to 28 reviews/case reports/

letters to the editor/descriptions in medical databases and an unquantifiable number of forum posts (Rauch et al. 2023). This highlights the ratio of robust scientific evidence to individual opinions and, in some cases, inadequately substantiated hypotheses (Mortimer and Zafren 2020). Numerous, sometimes contradictory, recommendations regarding the positioning of the rescued individual after removal from suspension have led to uncertainty in initial management in the past (Mortimer and Zafren 2020). The following detailed description of the pathophysiology aims to provide a comprehensible presentation of the current ICAR treatment recommendations (Rauch et al. 2023).

33.2 Pathophysiology

33.2.1 Pathophysiological Principles

Experimental studies have demonstrated venous blood pooling in the legs during suspension trials, caused by failure of the muscle pump during immobile hanging (Rauch et al. 2019, 2020). Apart from mild tachycardia and hypertension due to sympathetic activation in an uncomfortable suspended position, no changes in haemodynamics were observed, and particularly no change in stroke volume (Lanfranconi et al. 2017, 2019; Rauch et al. 2019; Stühlinger et al. 1972; Madsen et al. 1998; Shamsuzzaman et al. 1998). Therefore, the widely held hypothesis that this venous pooling leads to a reduction in cardiac preload, resulting in decreased cardiac output and thus unconsciousness, hepatic and renal injury (Patscheider 1972; Stühlinger et al. 1972) and ultimately cardiac arrest (Flora and Hölzl 1972) is increasingly unlikely.

Recent experiments rather suggest that a sudden onset of bradycardia and reduction in stroke volume, with a consequent collapse in blood pressure and thus cerebral hypoperfusion, leads to loss of consciousness (Rauch et al. 2019; Lanfranconi et al. 2017). These haemodynamic changes were usually preceded by presyncopal symptoms such as dizziness, confusion, pallor, cold sweating, visual disturbances, nausea and bradycardia (Rauch et al. 2019; Orzech et al. 1987; Madsen et al. 1998) and are very similar to a neurocardiogenic syncope (Lanfranconi et al. 2017, 2019; Rauch et al. 2019; Roeggla et al. 1996; Madsen et al. 1998; Shamsuzzaman et al. 1998; Beverly et al. 2019). However, the exact triggers of neurocardiogenic syncope and the relevance of orthostatic stress due to venous pooling remain unclear (Mosqueda-Garcia et al. 2000).

› *The pathophysiological mechanism leading to loss of consciousness in suspension syndrome is very similar to that of neurocardiogenic syncope.*

In contrast to a typical (neurocardiogenic) syncope, where the patient collapses to the ground and cerebral perfusion is rapidly restored by lying flat, resulting in quick recovery, there is no horizontal position during suspension (▣ Fig. 33.1). Thus, cerebral perfusion is not restored, the patient does not regain consciousness and may subsequently die. Additionally, airway obstruction due to hyperflexion or hyperextension of the head during suspension is possible (Kolb and Smith 2015).

Presyncopal symptoms demonstrated in experimental studies were characterised by considerable temporal variability, both in terms of onset and the beginning of loss of consciousness, and in some cases occurred after only a few minutes of free suspension (Lanfranconi et al. 2017, 2019; Rauch et al. 2019; Orzech et al. 1987; Madsen et al. 1998; Flora and Hölzl 1972; Mortimer 2011; Roeggla et al. 1996; Hsiao et al. 2012). Sex had no influence on the tolerated suspension

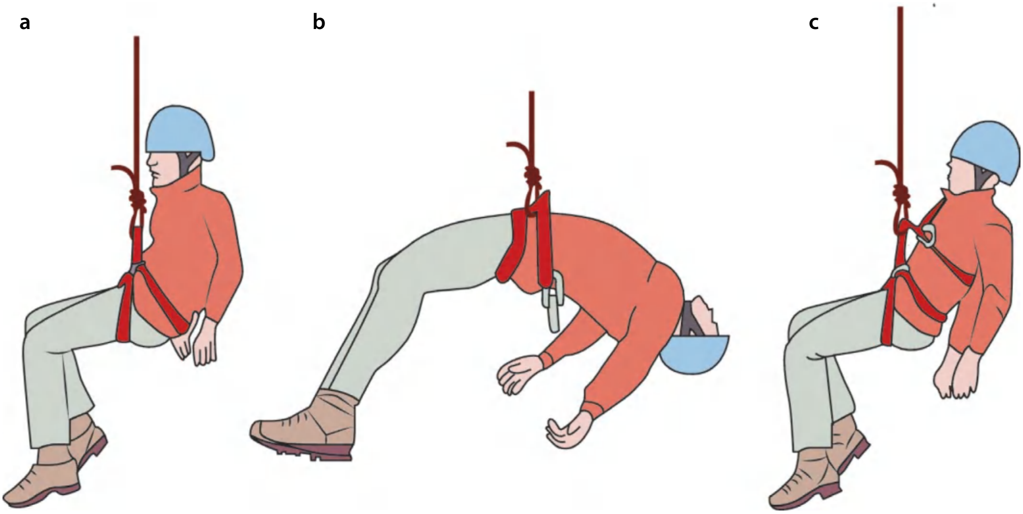


Fig. 33.1 Currently recommended harness systems in mountaineering. **a** Sit harness. **b** Suspension of an unconscious person in a sit harness. The return flow of blood from the lower body to the brain is insufficient against gravity, as the attachment point is higher. **c** Chest-sit harness combination. (From Lechner et al. 2024)

time in studies, whereas a high body mass index or physical exertion prior to suspension may reduce the time to onset of initial symptoms (Rauch et al. 2019; Turner et al. 2008; Hsiao et al. 2012). Similarly, pain-induced vagal reactions and other conditions such as trauma, blood loss, dehydration, hypothermia and hypoglycaemia can negatively affect the tolerated suspension time (Rauch et al. 2019; Mortimer 2011).

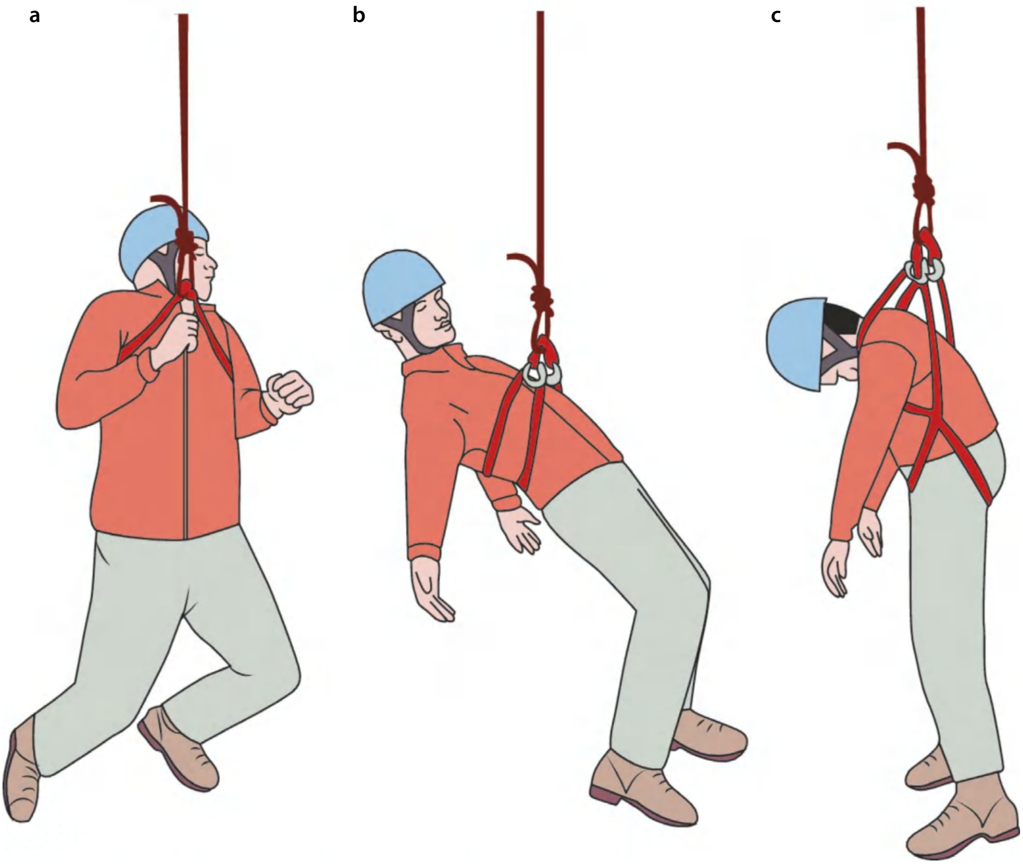
Apart from the described cardiocirculatory changes, prolonged suspension can induce numerous pathological changes due to tissue hypoxia. Rhabdomyolysis with hyperkalaemia (Wharton and Mortimer 2011; Beverly et al. 2019), renal injury (Stühlinger et al. 1972; Patscheider 1972), hepatic injury (Patscheider 1972), and nerve damage have been reported (Scharfetter 1972; Orzech et al. 1987). Accidental hypothermia due to unprotected exposure to environmental conditions (Mortimer 2011) and thromboembolic events due to venous stasis are also possible (Pisati et al. 2007; Rauch et al. 2020).

33.2.2 Rescue Death

At the second International Mountain Rescue Physicians' Conference, the expert consensus at the time recommended that, following rescue from the rope, patients should not initially be placed in a supine position, noting that the pathophysiology of suspension syndrome was not yet fully understood and that these recommendations should therefore serve as a basis for discussion (Flora et al. 1972). The rationale behind this recommendation was the concern that supine positioning could trigger acute cardiac volume overload due to blood returning from the legs. This was considered the cause of the rare deaths occurring in close temporal association after rescue from the rope (Flora and Hölzl 1972; Mortimer 2011). From the 2000s onwards, this recommendation was increasingly questioned (Adisesh et al. 2009). As experimental studies failed to demonstrate cardiac volume overload following supine positioning after suspension, this recommendation was first abandoned in the UK and the USA and has since also been discontinued in the Alpine region (Mortimer and Zafren 2020). Currently, ICAR recommends standard supine positioning after rescue from suspension (Rauch et al. 2023). At present, thromboembolic events or hyperkalaemia-induced cardiac arrhythmias are considered the most likely causes of death occurring immediately after rescue (Mortimer 2011).

33.2.3 Harness Systems

The type of rope attachment influences suspension on the rope. When suspended in a safety belt, a chest harness alone, or after direct attachment of the rope around the abdomen or chest, severe pain and nerve compression injuries occur within just a few minutes (◘ Fig. 33.2) (Stühlinger et al. 1972; Orzech et al. 1987; Roeggla et al.



◘ **Fig. 33.2** Attachment systems uncommon or not recommended in mountaineering: **a** Chest harness alone. **b** Safety belt (without leg loops). **c** Combination harness with a dorsal attachment point, as used, for example, in industrial climbing. (From Lechner et al. 2024)

1996; Scharfetter 1972). Suspension in a chest harness alone also leads to reduced vital capacity and may result in death due to compressive asphyxia (Roeggla et al. 1996; Mortimer 2011). These attachment methods are therefore obsolete but were standard in early case reports (Flora and Hölzl 1972).

In industrial climbing, harnesses with a dorsal attachment point are often used (◘ Fig. 33.2), for which some studies have reported reduced suspension tolerance (Beverly et al. 2019; Turner et al. 2008). This is explained by a more vertical suspension position and possible compression of the femoral vessels, which increases venous pooling. In addition, self-rescue is more difficult due to the poorly accessible dorsal attachment point.

However, these attachment methods must be distinguished from suspension in modern, well-fitted (chest) sit harnesses as used today in mountaineering (◘ Fig. 33.1). The leg loops of modern sit harnesses do not compress the femoral vessels (Mortimer 2011). The recommendation, occasionally found in the literature, not to remove the harness after rescue in order to prevent a sudden return of blood from the legs, is therefore not anatomically plausible (Seddon 2002; Mortimer 2011). The decision to leave the harness on or remove it should be based solely on rescue technical considerations (Mortimer 2011).

However, a poorly fitting sit harness can cause compression of the sciatic nerve, leading to sensory disturbances, restricted mobility and pain (Rauch et al. 2019; Orzech et al. 1987). Pain may also trigger a vasovagal syncope (Hsiao et al. 2012; Chen-Scarabelli and Scarabelli 2004).

33.3 Prevention

To best prevent suspension syndrome, various preventive aspects must be considered. Anyone present in an environment where free suspension with rope protection is possible must be aware of the risk of suspension syndrome. As described in ▶ Sect. 33.2, suspension syndrome can occur suddenly and at any time, so the duration of free suspension should be kept as short as possible. Therefore, self-rescue skills are essential, and the necessary equipment (e.g. accessory cord) must be carried (Mortimer 2011). To ensure the fastest possible rescue by companions, rope-protected activities should never be carried out alone.

To reduce venous blood pooling by increasing venous return to the heart, the muscle pump should be activated by moving the legs (Rauch et al. 2019). This can be achieved by moving freely in the air ('air cycling'), repeatedly pushing off nearby structures (e.g. rock, crevice wall), or standing up in a foot loop (◘ Fig. 33.3).

> *Activation of the leg muscle pump is the key measure to reduce venous pooling.*

A rucksack should be removed and, for example, secured at the attachment point to increase freedom of movement and make suspension more comfortable and less strenuous. In addition, the suspension position can be optimised by using slings under the knees (Madsen et al. 1998; Turner et al. 2008) and/or under the armpits (◘ Fig. 33.3). It is important to ensure that the sling does not cut into the skin, so it should be as wide as possible and, if necessary, padded. If these measures cannot be implemented, the first rescuer should lift the patient's legs to achieve a more horizontal suspension position and stabilise the head.

The harness system used should be properly adjusted to the body size, and a suspension test with equipment should be performed before purchase to ensure the most pain-free suspension possible (Hsiao et al. 2012).

A person immobilised on a rope is an emergency, and the situation must not be underestimated. If self-rescue or rescue by companions is not possible, an emergency call must be made without delay.

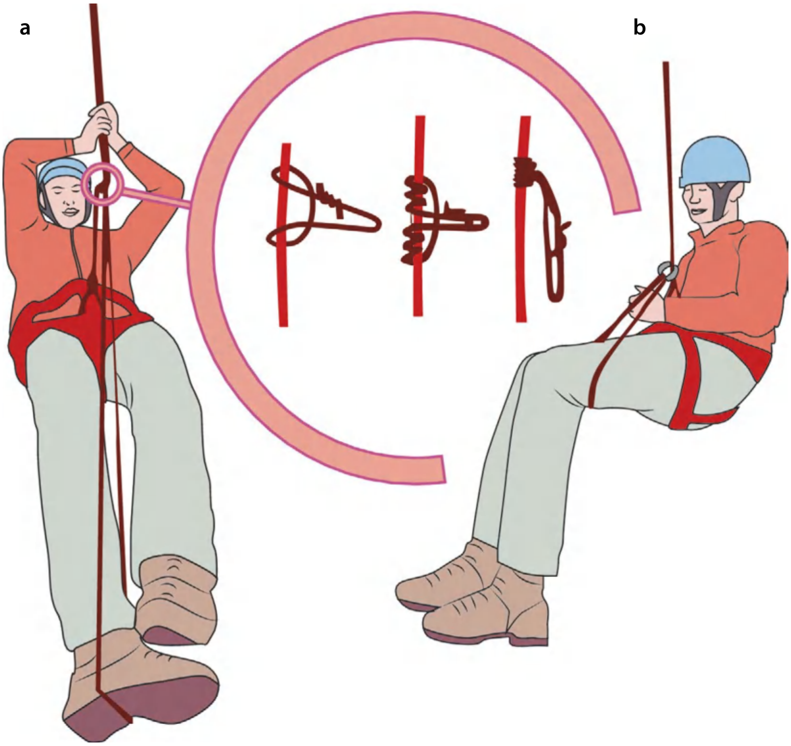


Fig. 33.3 Prophylaxis of suspension syndrome. **a** Activation of the muscle pump by repeatedly standing up in a foot loop (here fixed with a Prusik knot). **b** Improvement of venous return by elevating the legs. (From Lechner et al. 2024)

33.4 Therapy

As rope protection, and thus suspension syndrome, predominantly occur in areas with an increased risk of falling, rescue personnel must be protected against falls and objective alpine hazards. The preventive measures listed in ► Sect. 33.3. (activation of the muscle pump, optimisation of suspension position) should be initiated by the first rescuers on scene in parallel with the rescue of the casualty.

Treatment after release from the suspension position is carried out according to standard emergency medical algorithms. A specific positioning therapy, in particular avoiding initial supine positioning, is no longer recommended (Adisesh et al. 2009, 2011; Mortimer 2011; Thomassen et al. 2009).

As part of the assessment of vital parameters, an ECG should be performed promptly to rapidly diagnose signs of hyperkalaemia (flattened/absent P waves and first-degree AV block, broad QRS complex, peaked T waves, ST segment depression) and cardiac arrhythmias (bradycardia, ventricular tachycardia, cardiac arrest) (Lott et al. 2021). In haemodynamically unstable patients, suspected hyperkalaemia should be treated according to current guidelines (10 ml 10% calcium chloride or 30 ml 10% calcium gluconate i.v. salbutamol 10–20 mg inhaled, transfer to hospital for glucose/insulin administration and, if necessary, dialysis (Lott et al. 2021). Medications such as succinylcholine, which increase serum potassium, should be avoided.

Portable ultrasound can be used to detect deep vein thrombosis of the leg or right heart strain in suspected pulmonary embolism, and in trauma patients, an eFAST (extended focused assessment with sonography for trauma) can be performed (Rauch et al. 2023). Accidental hypothermia should also be ruled out (Paal et al. 2022).

If suspension syndrome leads to prolonged end-organ hypoperfusion, cardiac arrest may occur in the terminal stage. In this case, standardised cardiopulmonary resuscitation according to current guidelines should be performed (Soar et al. 2021). The most likely reversible causes of cardiac arrest are hyperkalaemia, pulmonary embolism, hypothermia and hypoxia due to airway obstruction during suspension (Wharton and Mortimer 2011; Mortimer 2011; Rauch et al. 2020; Kolb and Smith 2015).

In the hospital, a structured patient assessment including necessary imaging should be performed. Liver and renal function, as well as creatine kinase and myoglobin levels, should be monitored to detect possible rhabdomyolysis at an early stage (Mortimer 2011; Wharton and Mortimer 2011; Patscheider 1972; Stühlinger et al. 1972). The risk increases with suspension time and becomes clinically relevant after a duration of 2 h at the most (Flora and Hölzl 1972; Mortimer 2011; Wharton and Mortimer 2011). Nerve compression injuries caused by the harness are possible (Orzech et al. 1987; Rauch et al. 2019).

33.5 ICAR Recommendations

Based on the ICAR recommendations for suspension syndrome, the following summary recommendations for the prevention and management of suspension syndrome can be made (supplemented after Rauch et al. 2023).

ICAR Recommendations for the Prevention and Management of Suspension Syndrome

- Rope work should never be conducted alone.
- Persons suspended in a harness should be rescued as soon as possible, even if the casualty is asymptomatic, as time to near or actual syncope and cardiac arrest is variable and unpredictable.
- While awaiting rescue, persons suspended freely on a rope should move their legs to reduce venous pooling.
- If no adjoining structures are in reach, foot loops should be used to step in and increase the activation of the muscle pump.
- A rucksack should be removed and, for example, secured at the attachment point.
- If the casualty is no longer able to act and it is safe to do so, the first rescuer reaching the casualty should raise the victim's legs to create a more horizontal position while measures are taken to lower the casualty to the ground.
- Once the casualty is on the ground, they should be positioned supine. Assessment and treatment should follow standard advanced life support algorithms. An ECG should be performed promptly to detect cardiac arrhythmias and signs of hyperkalaemia.
- Reversible causes of cardiac arrest, including hyperkalaemia and pulmonary embolism, should be considered and managed appropriately.
- After prolonged hanging (>2 h), monitoring of serum potassium and creatine kinase should be established and renal replacement therapy considered in patients with acute kidney injury.
- Modern seat harnesses have no effect on the blood circulation in the legs. The decision to remove them should therefore be made solely based on rescue technical considerations.

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34

Mountain Rescue Techniques for Mountain and High-Altitude Medicine Practitioners

Walter Zörer

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'Assistance from companions in mountain emergencies can save lives.' (Klaus 2019). In any emergency situation in the mountains, the fastest help can only be provided by companions. By the time an organised rescue operation by mountain rescue services or mountain patrol arrives, valuable time has often already passed. Moreover, even in areas with excellent rescue infrastructure, an organised rescue operation is not always possible, leaving injured mountaineers to rely on themselves. The essential basic techniques of summer and winter mountaineering, as well as fundamental rescue techniques, should be standard for every mountain and high-altitude medicine practitioner. Since mountaineering cannot be learned solely from books, attending appropriate training courses and regular practice and repetition are necessary to be able to apply these skills effectively in an emergency.

Measures to Reduce Risk in Mountain Sports

- Training of mental and physical skills.
- Mastery of rope, belaying and rescue techniques.
- Route planning.

The aim of this guide is to equip the user with the tools for efficient companion rescue using the simplest possible means. These techniques are also taught and practised in training courses for mountain medicine practitioners. This ensures that mountain competencies are taught in a structured manner and are also included in relevant examinations.

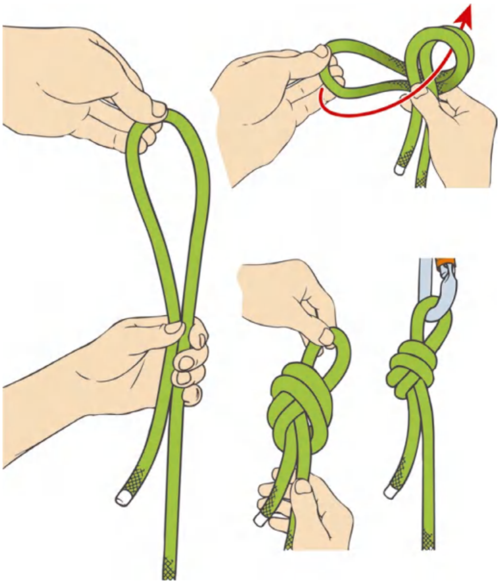
34.1 Knots and Rope Attachment

Just a handful of knots are needed to perform all applications in the mountains. This section focuses on the most important types of knots that are essential. The main emphasis is on the safe mastery of the knots and their correct execution.

34.1.1 Knots

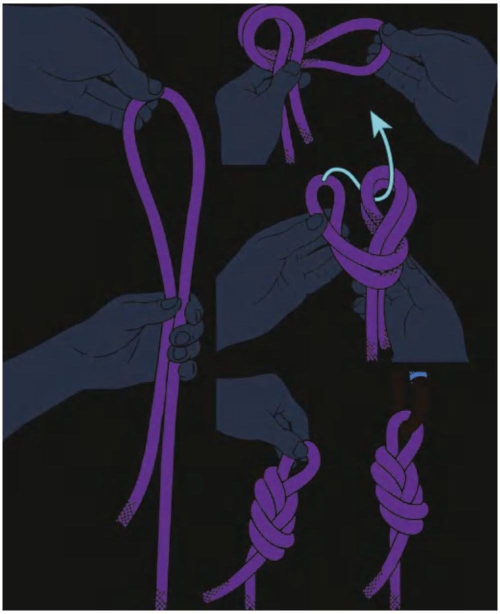
- **Overhand Knot**

Universal knot for various applications.



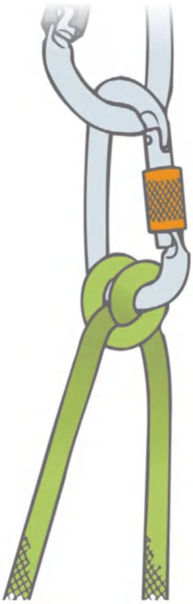
- **Figure-of-Eight Knot**

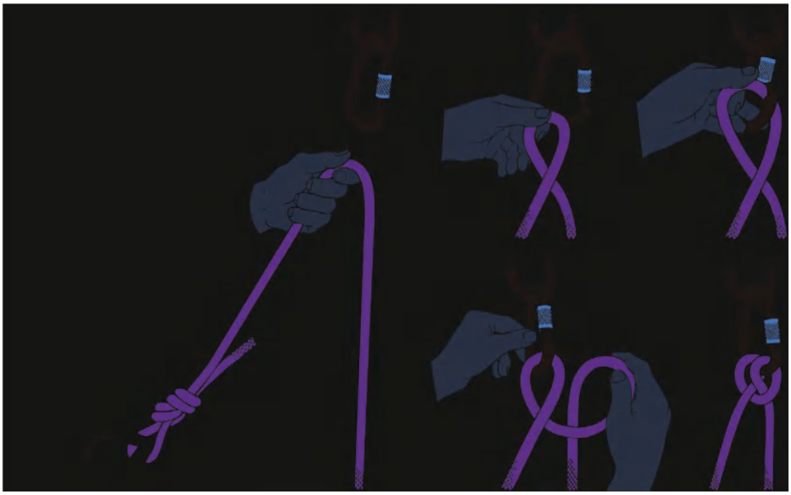
Typical knot for tying in.



- **Clove Hitch**

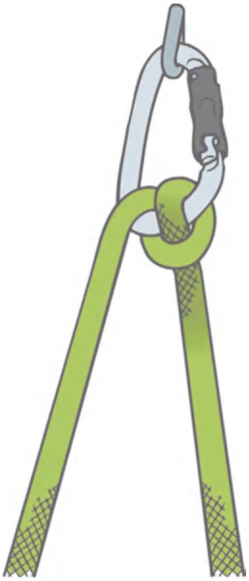
Used for self-belay at the belay station, amongst other things.

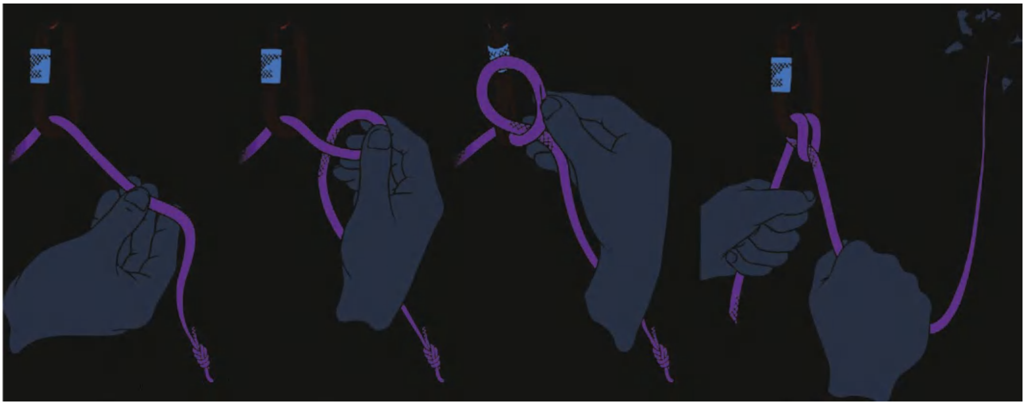




■ Crossing Hitch (Italian Hitch)

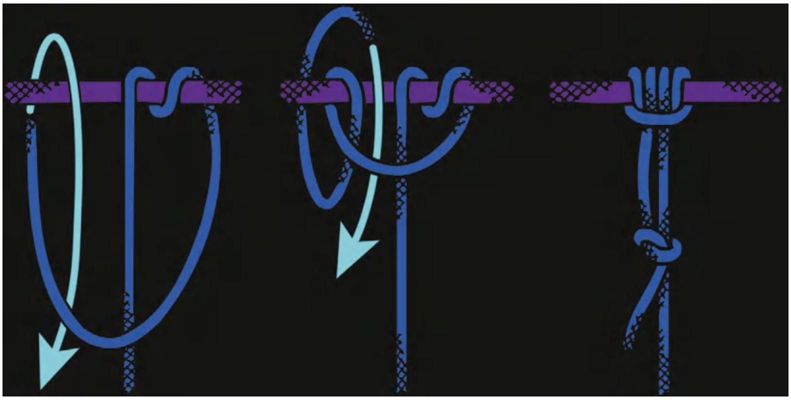
Universal braking and belaying knot.





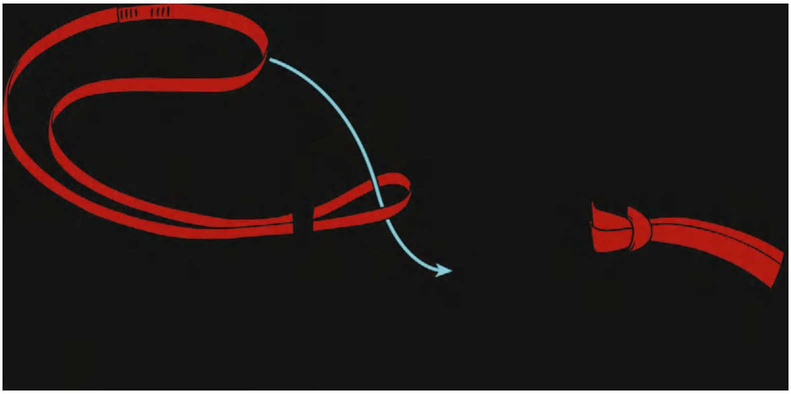
Prusik Knot

Friction knot for various applications.



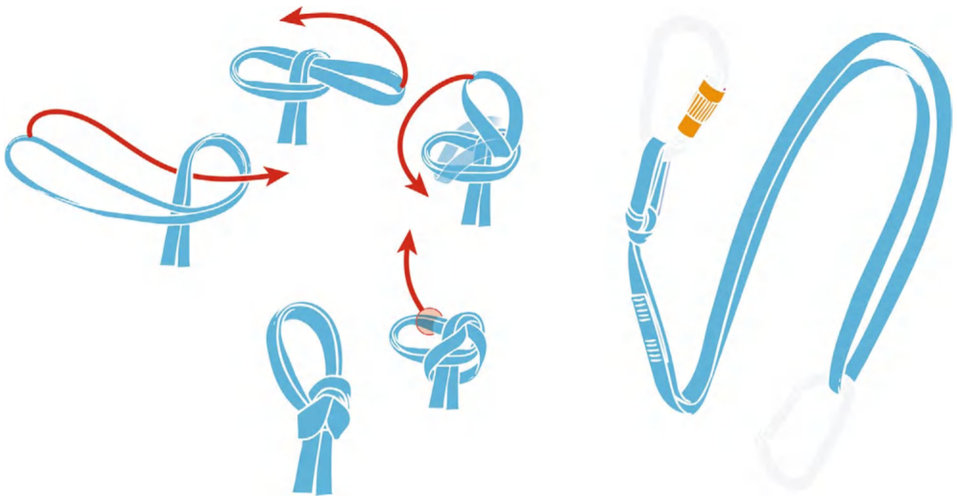
Girth Hitch

For attaching the personal safety sling to the climbing harness.



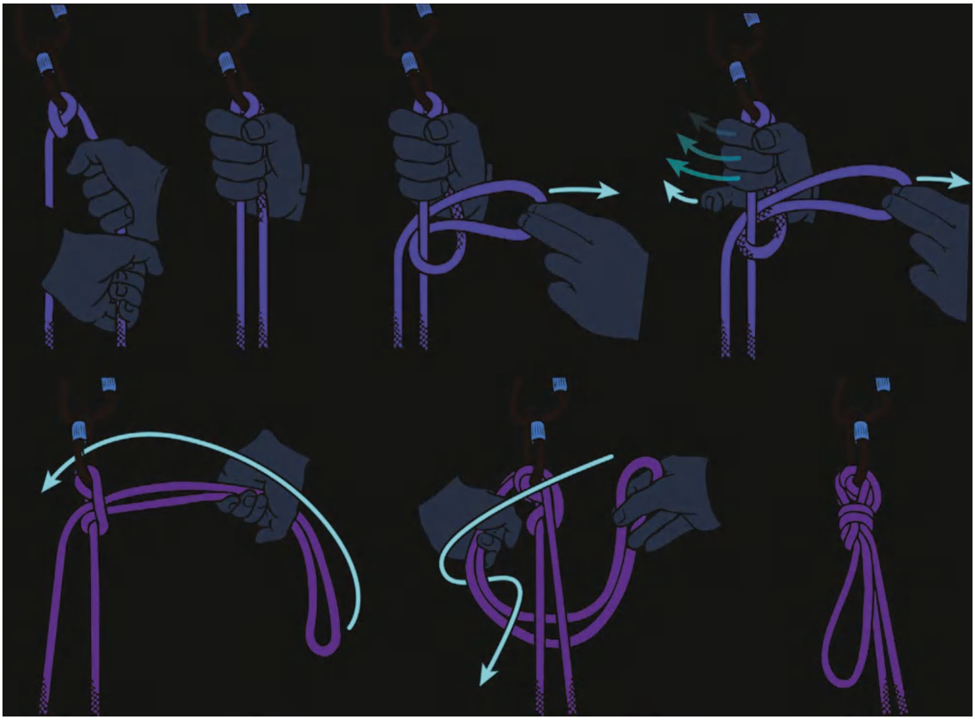
Bowline on the Bight (Double Bowline)

Mainly used in building belay stations.



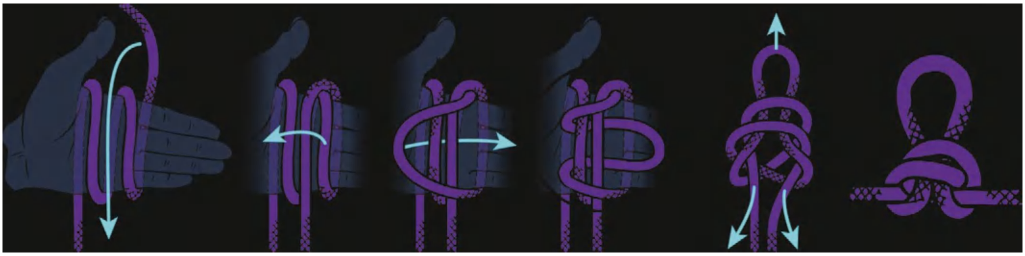
Tie off the Italian Hitch

For securing, e.g. a Crossing Hitch (Italian Hitch).



- **Alpine Butterfly Knot**

Braking knot for glacier rope teams.



34.1.2 Rope Up

Depending on the type of mountain activity, there are various methods of roping up. For mountain climbing, the figure-eight knot is used, whilst in sport climbing, the double bowline knot may also be an option.

For glacier travel, the figure-eight loop in combination with a so-called safebiner (a locking carabiner with an especially secure locking mechanism that reliably prevents accidental opening) has proven effective.

To reduce the risk of falling into a crevasse, snow-covered glacier surfaces should always be crossed as a roped team. The spacing between climbers is adjusted according to the number of mountaineers, with a team of three forming the minimum unit. Under certain snow conditions, the use of friction knots may also be advisable (note: in such cases, it is essential to learn the specific rescue techniques required to bypass these knots).

34.2 Belay Point and Belaying Techniques

In climbing, the belay point is of particular importance. An intermediate anchor may fail without causing the entire team to fall, but the belay point itself must never fail and must always be able to withstand the expected forces with absolute certainty. By connecting two or more anchor points, redundancy is achieved to meet this requirement. On frequently climbed routes, bolted anchors are often already in place at the belay point, which makes things easier. Such solid anchor points (such as a substantial rock thread, for example) are connected using a serial anchor system.

34.2.1 Serial Anchoring in Rock

The central point (double bowline) is fixed to the lower anchor point with a locking carabiner. The remainder of the sling is attached to the higher anchor point using a locking carabiner and a clove hitch, without any slack.

34.2.2 Belay Point

Central point carabiner, Italian Hitch at the central point, personal anchor with a clove hitch in a separate carabiner.

NB: When climbing multi-pitch routes, body belaying is only used for the first pitch from the ground (with available belay devices) or when climbing a crag. In mountainous terrain, always belay from the belay point.

34.2.3 Belay Point Variations in Ice and Snow

34.2.3.1 Serial Anchoring in Ice

- **Abalakov Thread—Ice Thread**

The ice thread is particularly useful for retreat or abseiling, providing a reliable anchor point. The strength depends on the quality of the ice and the depth of the thread. To achieve sufficient strength, ice screws at least 19 cm in length should be used for drilling. The accessory cord used should be made of Dyneema or be a half-rope segment. The holes are drilled at approximately 90° to the ice surface and at an angle of about 60°. An ice threader is used to pull the cord through. The ends are joined with a double overhand knot.

Deadman Anchors with Ice Axe in Snow
The holding strength of all anchor points in snow depends primarily on the snow conditions and is often difficult to assess. The most reliable method remains the Deadman anchor.

- **Equalised Anchor with Skis**

In winter, skis are the first choice for constructing an anchor after a crevasse fall.

34.2.4 Abseiling

In general, there are two types of abseiling.

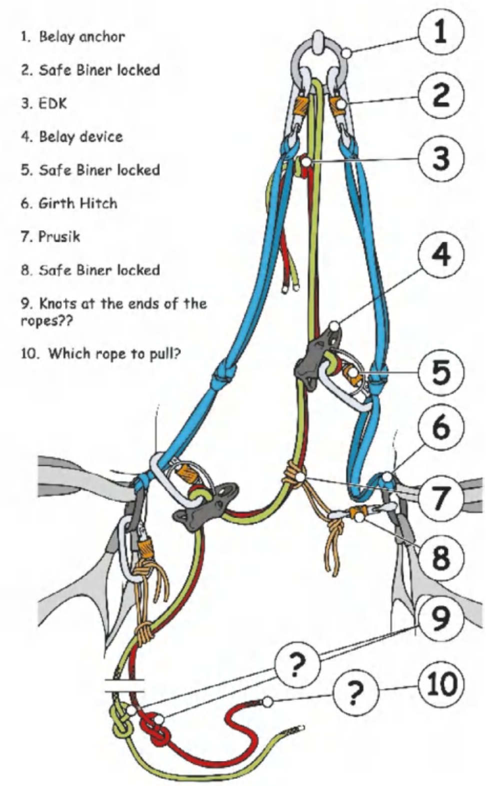
- **To Lower Someone by Abseiling**

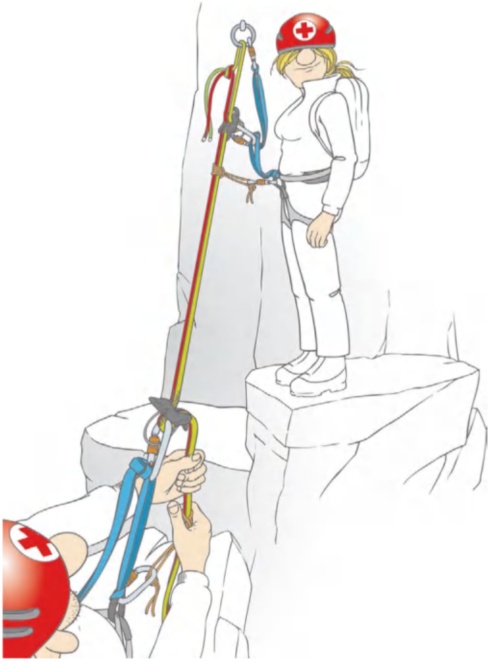
The rope partner is lowered to the next belay point or to the ground using a belay device (e.g. Italian hitch). The belayer ensures a smooth and terrain-appropriate descent. The rope remains taut at all times, and the descent ends at the next secure point.

- **Abseiling**

At the start of the abseil, all participants prepare a personal safety sling (120 cm sewn sling) with a belay device, safety carabiner, and one Prusik loop.

The Prusik is attached to the central point of the harness, as is the personal safety sling. If there are several people at the belay, all should, if possible, be clipped into the rope with a descender device and Prusik.





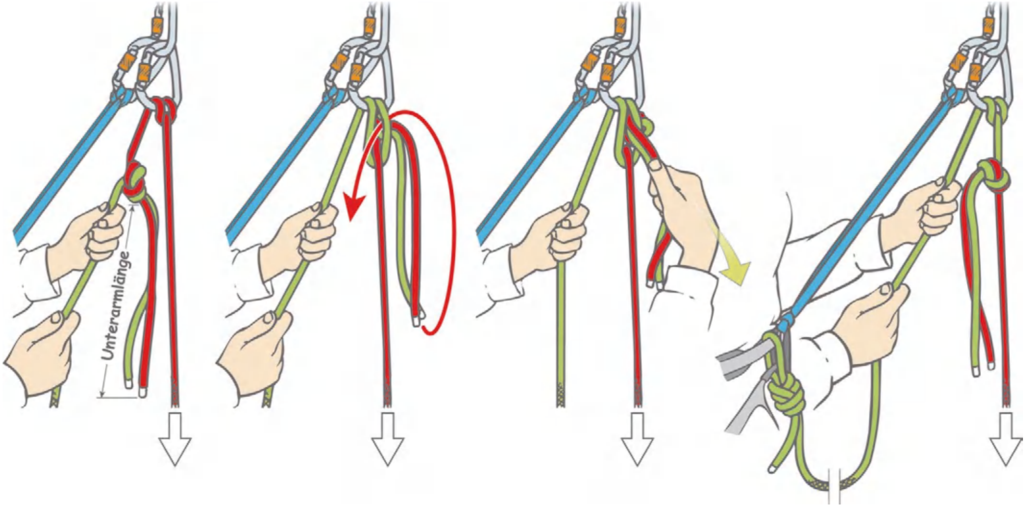
Standard Procedures for Active Abseiling

- System check **before** unclipping the personal safety sling at the belay.
- Knot at the end of the rope (each rope individually).
- The joining knot (European Death Knot (EDK)) should be on the inside (rock side) to prevent snagging when pulling the rope down.

34.2.5 Rope Extension

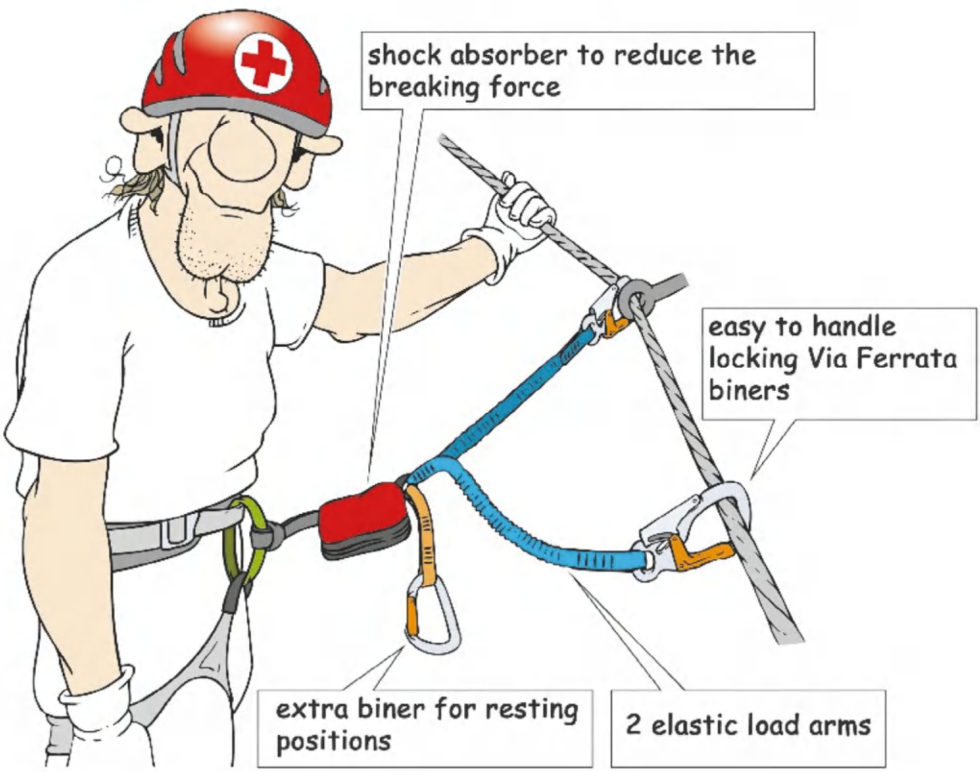
In order to lower an injured person more than one rope length, two ropes must be joined together. There are several methods for rope extension; one of the simplest, when only one person is on the rope, is to let the knot pass through the belay device.

The ropes are joined with a European Death Knot (EDK), and the ends should be at least the length of a forearm. This knot passes directly through the Italian Hitch knot when lowering (provided the pear-shaped HMS carabiner is not too small!). To assist, the loose ends are threaded through the HMS carabiner before the EDK knot.

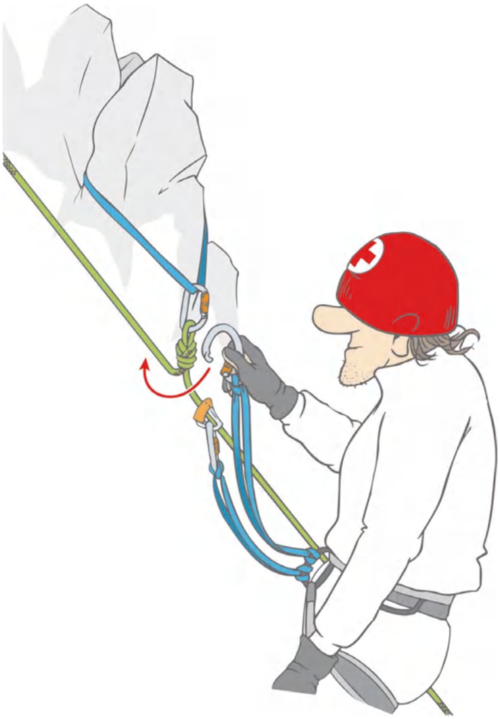


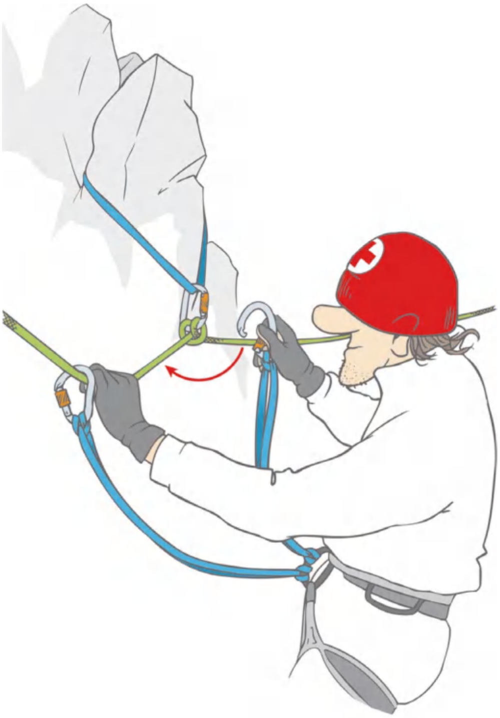
34.2.6 Using Fixed Ropes and Via Ferrata

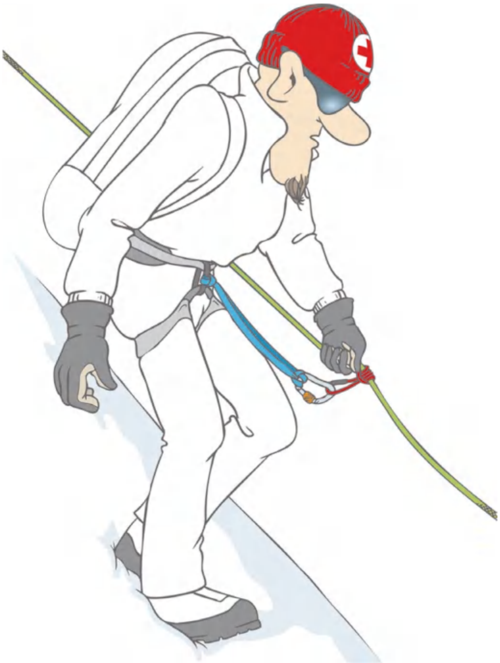
For via ferrata, it is essential to use a certified via ferrata set.


shock absorber to reduce the breaking force
easy to handle locking Via Ferrata biners
extra biner for resting positions
2 elastic load arms

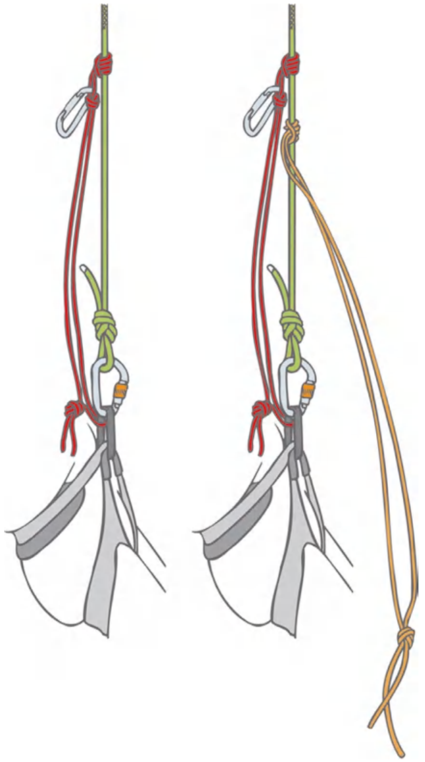
On high-altitude tours, ski mountaineering trips and expeditions, certain sections may be secured with fixed ropes. These are traversed using a personal safety sling. For steep ascents and descents, the use of ascenders or Prusik knots is recommended.







34.3 Rescue Techniques

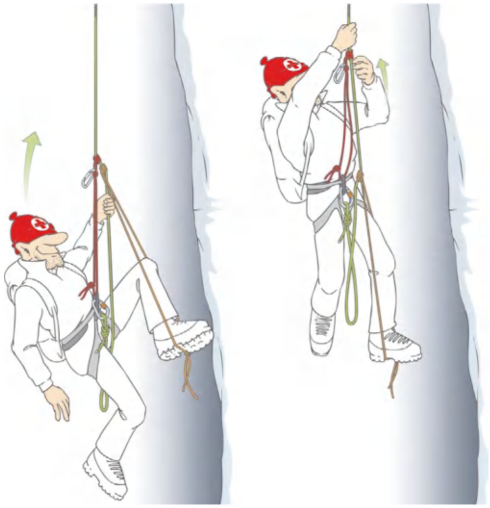


Mountaineering in any form involves numerous risks on a daily basis. This is part of the appeal for alpinists, but these risks should be managed. Since mistakes are generally unplanned, it is always unforeseen incidents that present challenges in the mountains and can put groups in distress. Often, it is inadequate equipment, lack of rope skills, and absence of survival techniques that lead to—often avoidable—catastrophes. Every properly trained mountaineer should be able to handle most situations independently.

34.3.1 Self-Rescue

In the event of a crevasse fall, it is essential to exit the crevasse quickly and efficiently. Assuming that companions were able to arrest the fall but do not know rescue techniques or cannot set up an anchor, self-rescue is the only option.

- **Prusik (Including the Münchhausen Technique)**



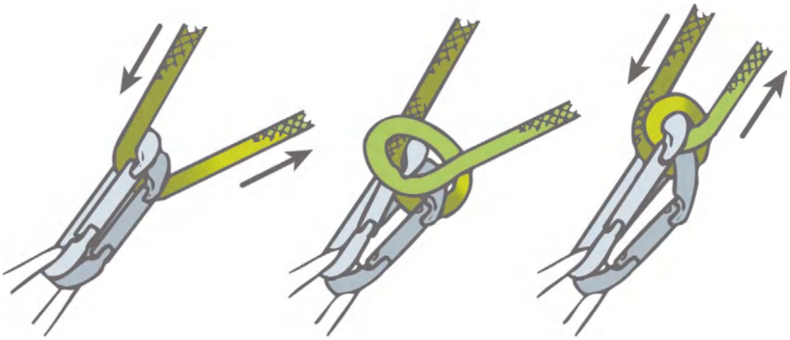
In the minimal version, two accessory cords (approx. 1 × 1.5 m and 1 × 5 m) and three carabiners are sufficient to ascend the rope out of the crevasse.

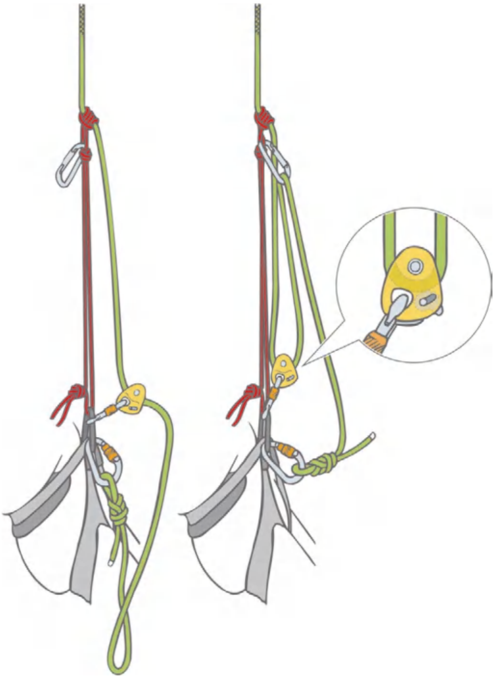
The shorter cord is attached to the rope with a Prusik and tied to the tie-in point with a figure-eight knot. The longer cord is attached below the first with a Prusik. In preparation for the ‘Münchhausen technique’ at the crevasse edge, an EDK is tied as close as possible to the Prusik and a carabiner is clipped in. The ends of the cord are passed under the boot and tied with an EDK to form a clove hitch around the boot. This creates a foot loop.

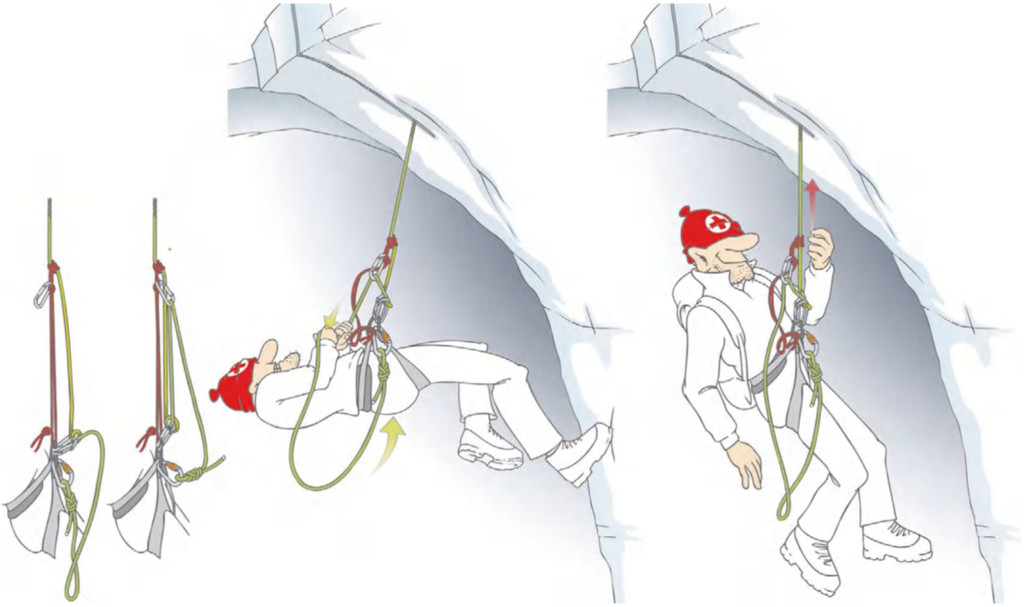
Once the crevasse edge has been reached using this ascent technique, the Münchhausen technique must be employed.

To do this, an ascender (such as a Garda hitch, Tibloc, Micro Traxion, etc.) is installed at the tie-in point. The rope runs through the ascender and is clipped into the (prepared) carabiner at the upper Prusik knot. This creates a pulley system, which allows the exit over the crevasse edge.

The foot sling can now be removed, and proceed beyond the crevasse edge.

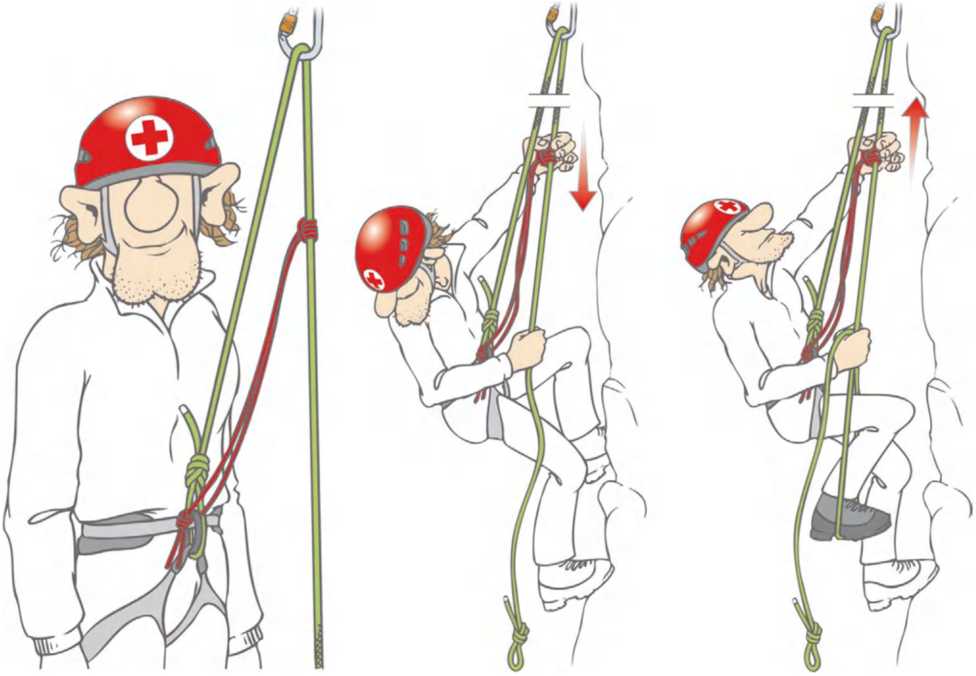






Rope Pulley

In situations where descending and re-ascending the rope is necessary, the rope pulley has proven effective. In this technique, the end of the rope is tied into the harness and redirected at the anchor. A Prusik knot (approximately forearm length) is attached to the redirected rope and secured to the tie-in point.

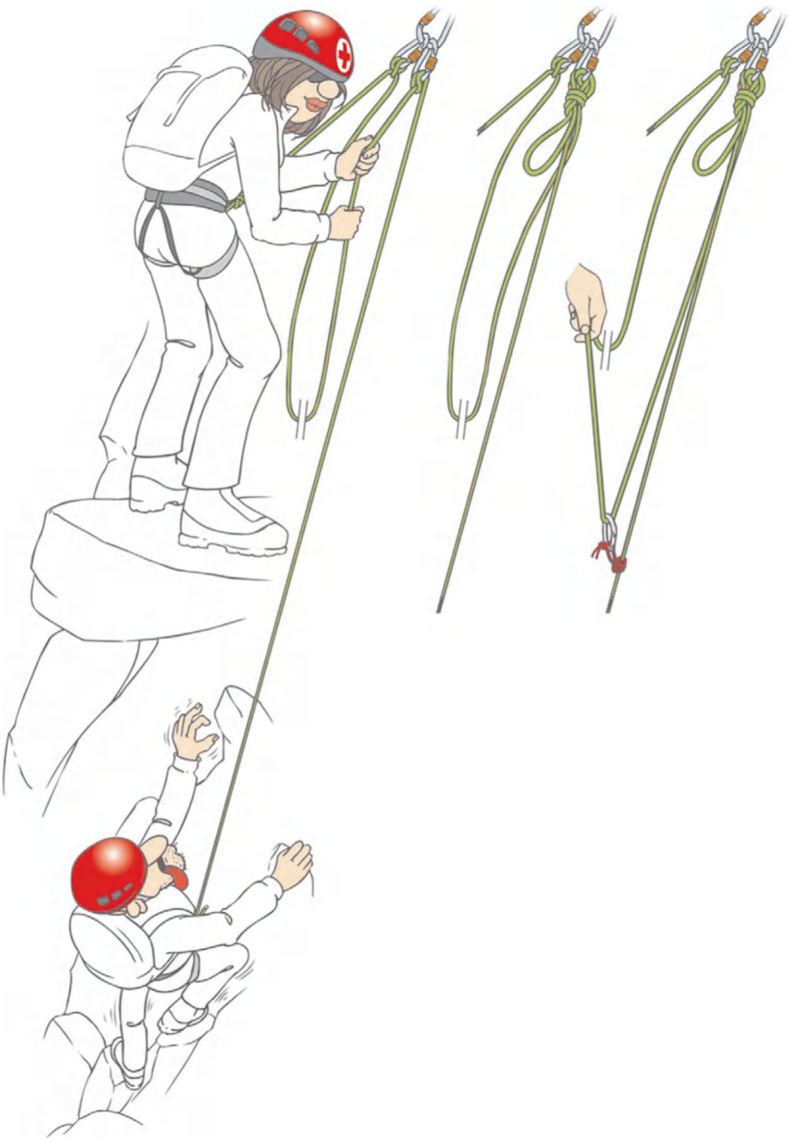


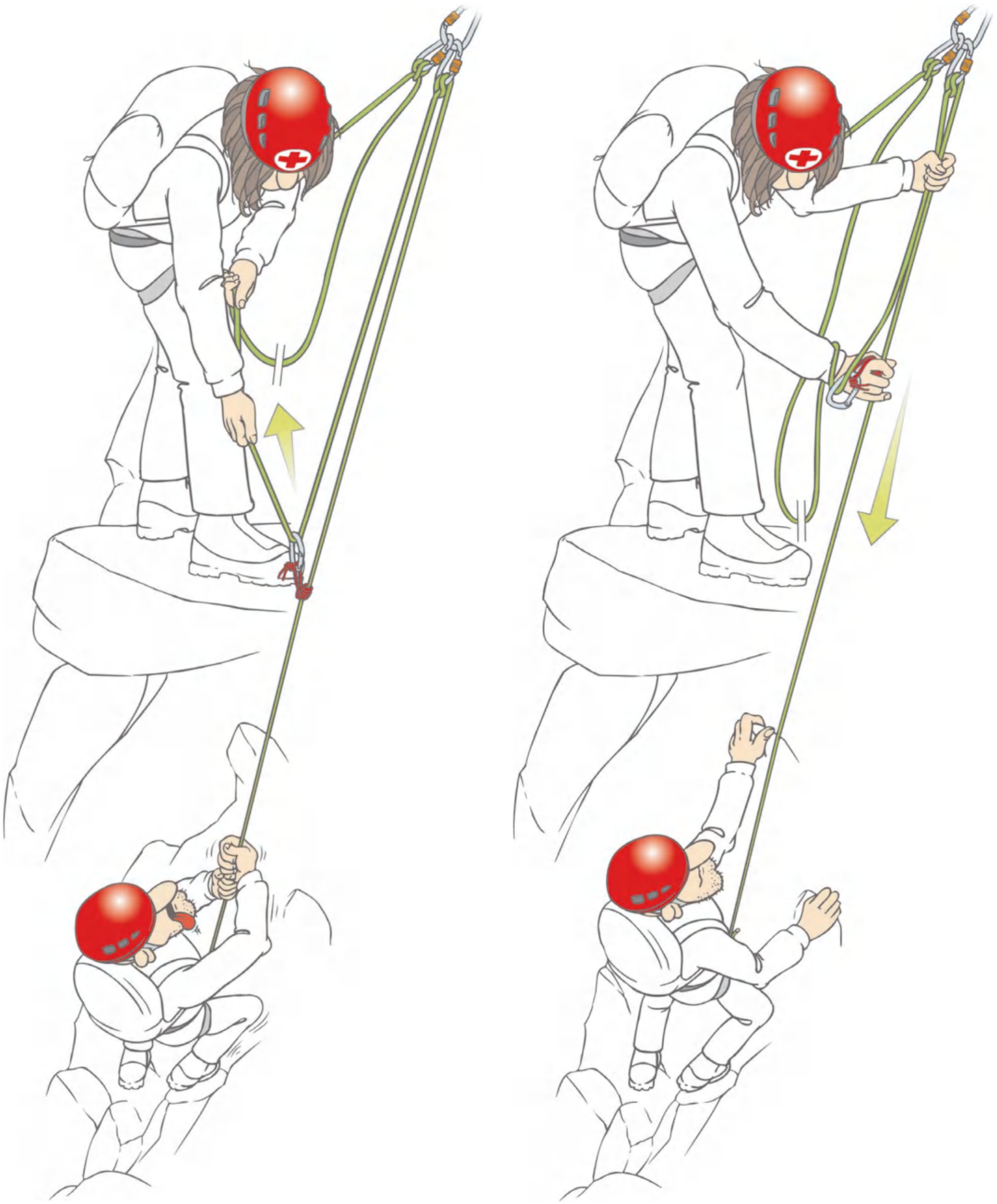
34.3.2 Companion Rescue

- **Haul System (Express Pulley)**

This simple and rapidly assembled system is primarily used to assist in hauling a second climber or in similar situations. It is unrealistic to use it for rescuing a person hanging freely in space.

First, the Italian Hitch is tied off. Next, a Prusik (or, for example, a Tibloc) is attached to the load rope, and the slack haul rope is redirected through a carabiner at this point. The Italian hitch is then released and hauling can begin, although friction is considerable. One hand is used to hold both ropes in place while the other advances the Prusik.

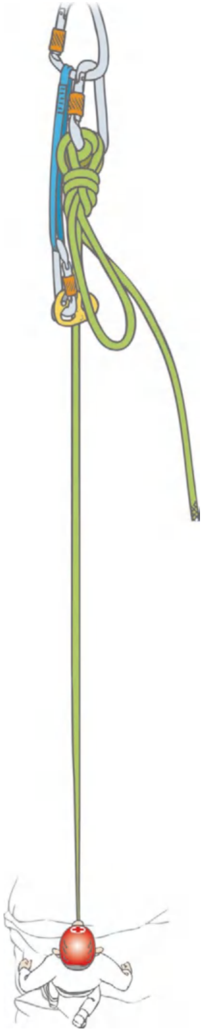


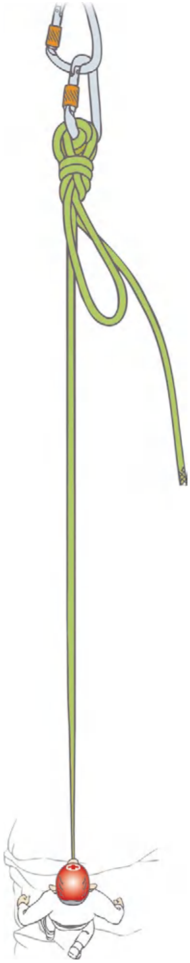


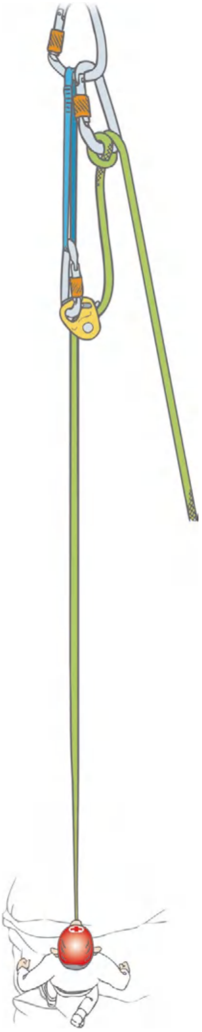
Pulley System with Micro Traxion

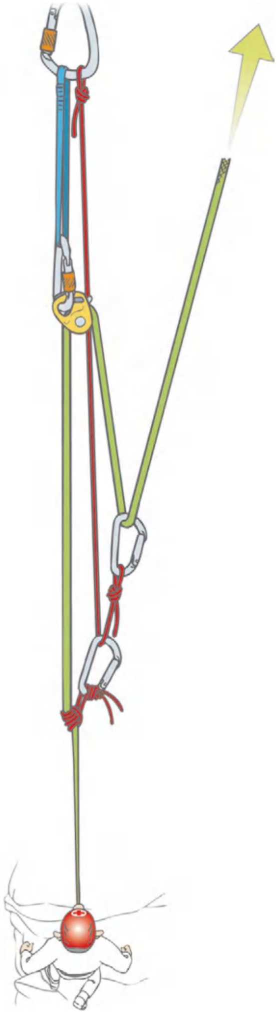
With a mechanical advantage of 1:5, the pulley system is one of the most efficient methods for hauling an injured climber upwards.

First, the Italian hitch is tied off. Then, a short sling with a Micro Traxion is attached to the anchor and the load rope. By subsequently releasing the Italian hitch, the load can be transferred to the pulley. As with the express pulley, a short Prusik with a carabiner is attached to the load rope. A cord (approx. 3 m) is then tied to the anchor with an EDK and threaded through the carabiner on the short Prusik. A carabiner is clipped into the resulting loop, through which the haul rope is now passed.



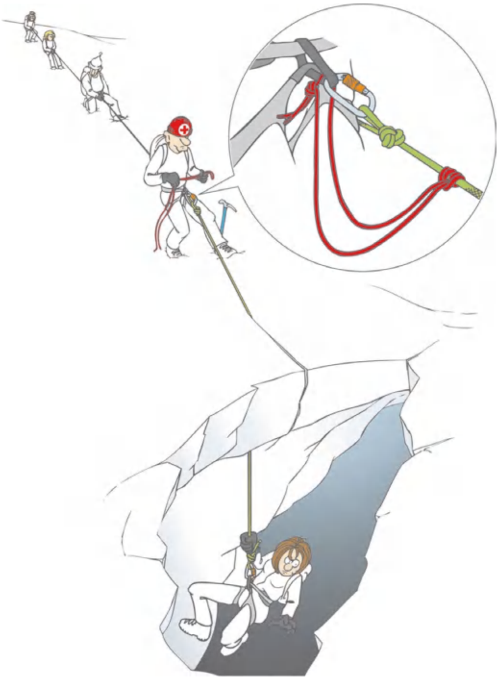


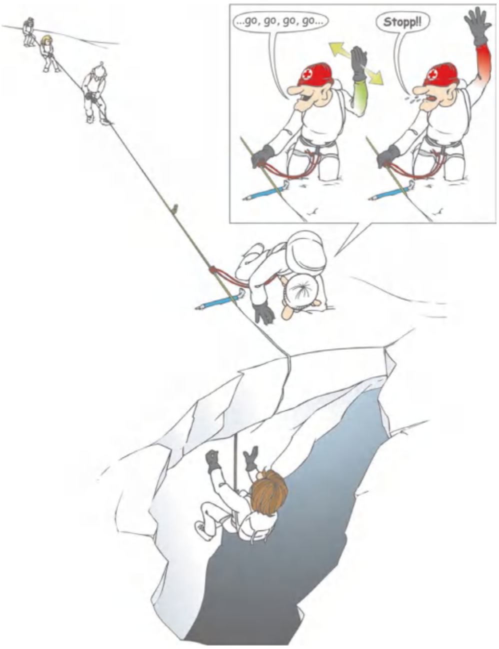




Team Haul (Crevasse Rescue with a Group)

With at least three to four rescuers or rope team members, the team haul is a quick and simple solution for crevasse rescue. The next person behind the fallen climber ties a Prusik to the load rope and connects it to their harness. The main rope knot can then be unclipped, and the rescuer can approach the crevasse edge to establish contact with the casualty. To reduce friction, an ice axe can be placed under the load rope. The rescuer at the crevasse edge then coordinates the hauling team and the casualty to prevent further injury during extraction. After the rescue, the rescuer returns to their knot and reattaches to the main rope.




…go, go, go, go…
Stopp!!

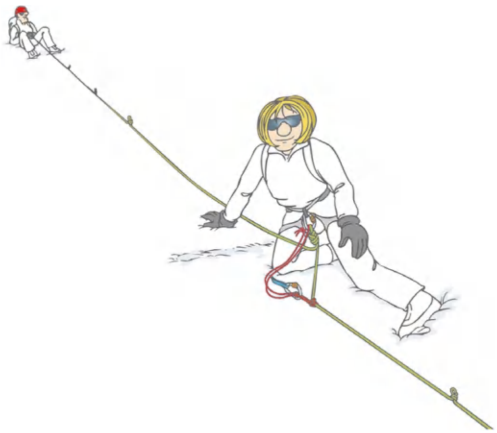
Pulley (Simple Pulley) in a Three-Person Rope Team

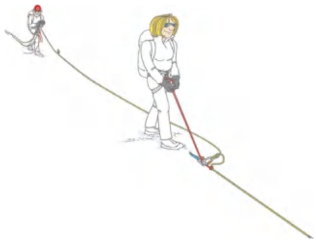
The standard rope team on a glacier consists of three people. In the event of a crevasse fall, the climber in the middle first builds an anchor (e.g. Deadman anchor, ski anchor, ice screw) to transfer the load. Using a long cord, a Prusik is attached to the load rope, the cord is tied off with an EDK as efficiently as possible and clipped into a locking carabiner at the anchor. The loose ends of the cord are attached to the tie-in point at the harness. The load can now be transferred by the third team member, slowly paying out rope. The middle climber can then unclip from the main rope and attach it directly to the anchor for redundancy. They remain at the anchor and provide additional security with their body weight.

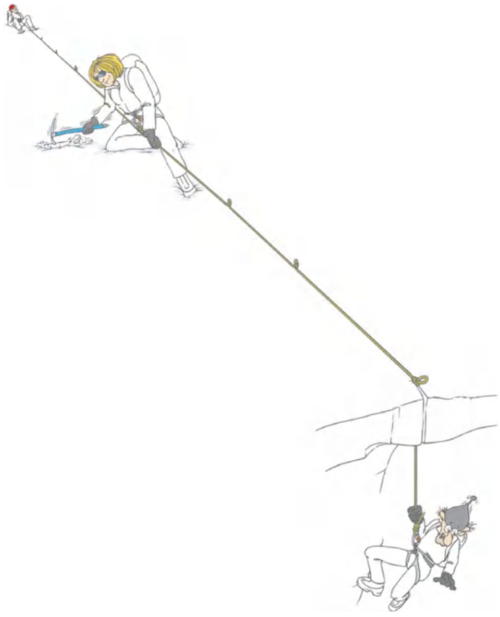
The rear climber (the rescuer) has meanwhile attached a Prusik with a cord approximately 3 m long to the slack rope (possibly with a figure-eight knot after the Prusik), secured a shortened branch (placed under the shoulder/armpit) to their harness and unclipped the rope. The rescuer can now advance the Prusik on the unloaded rope while moving towards the anchor, always remaining secured. After passing the anchor, they proceed to the crevasse edge to contact the casualty, bringing the Prusik.

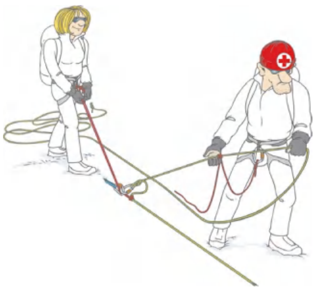
The slack rope is then used to lower a pulley with a carabiner to the casualty, who attaches it to their tie-in point. A Prusik is now tied onto the haul rope with the remaining free end, creating a progress capture.

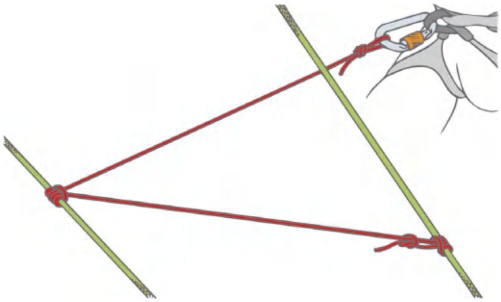
Now the casualty is hauled up directly by the rescuer standing at the edge of the crevasse, thereby avoiding additional friction over the edge. The victim can also assist by pulling on the main rope; ideally, the rescuer gives the command (Heave-ho!).

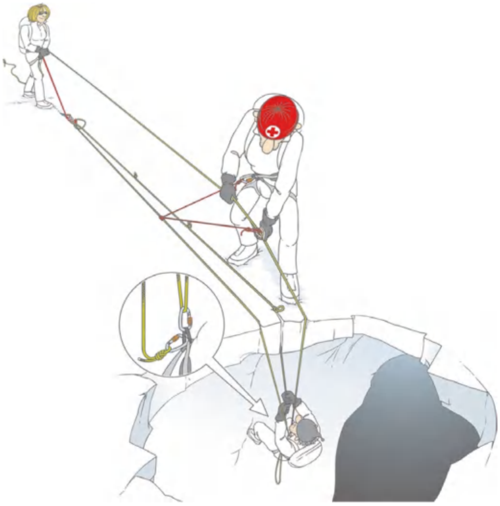






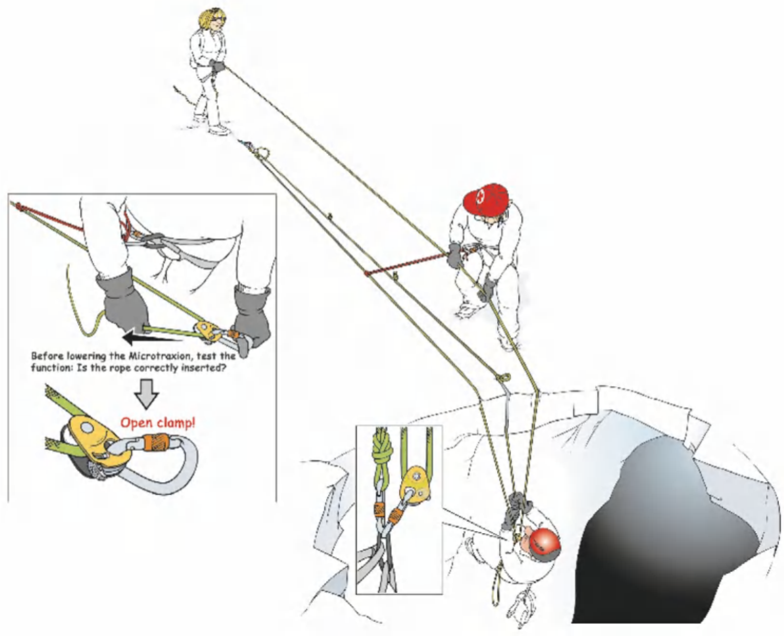






Tip

Instead of a carabiner, a Micro Traxion or similar device can be lowered to the casualty. This reduces friction and increases the efficiency of the progress-capture pulley.



Before lowering the Microtraxion, test the function: Is the rope correctly inserted?

Open clamp!

Reference

Klaus H (2019) Immediate life-saving rescue. In: Berghold F, Brugger H, Burtscher M, Domej W, Durrer B, Fischer R, Paal P, Schaffert W, Schobersberger W, Sumann G (eds) Alpine and altitude medicine. Springer, Berlin, pp 257–266. https://doi.org/10.1007/978-3-662-56396-0. isbn:978-3-662-56395-3

Analgesia in Mountainous Terrain

Peter Paal, Marc Moritz Berger, and Urs Pietsch

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Adequate analgesia is a fundamental right of the patient, and also serves as a simple, easily implemented, and tangible quality control measure for an effective emergency medical service. Sufficient analgesia is particularly important in mountainous environments, as evacuation can be more prolonged and complicated than in urban settings. Several hours may elapse during a complex rescue before definitive hospital care is reached. For these reasons, adequate analgesia should be provided in the mountains even more so than in urban areas. Effective prehospital analgesia is highly dependent on the qualifications of the rescuer. In alpine environments, adequate analgesia may be significantly hampered by additional challenges such as extreme cold, wind, logistical constraints, evacuation limitations, restricted monitoring and difficulties in establishing intravenous access (Ellerton et al. 2014).

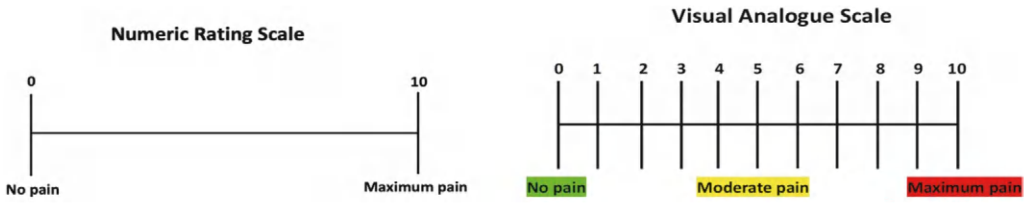
> › In mountainous terrain, many rescue personnel provide only insufficient pain management for patients. The use of a pain scale (e.g. Numerical Rating Scale [NRS] or Visual Analogue Scale [VAS]) (◘ Fig. 35.1) is recommended to quantify pain and document the effectiveness of analgesia. In addition, therapy protocols should be used to increase the efficiency and safety of analgesic management. Specific training in the recognition and treatment of pain should be established.

Analgesia can in principle be achieved using non-pharmacological methods, such as positioning and splinting (◘ Table 35.1) (Ellerton et al. 2009), and, with sufficient medical expertise, also with pharmacological agents (◘ Fig. 35.2). Non-pharmacological analgesia offers numerous advantages (◘ Table 35.2) and should therefore be used as basic analgesia in all trauma patients.

> › The importance of non-pharmacological therapy should be emphasised.

In pharmacological analgesia, a distinction is made between the well-established systemic analgesia in the Alpine region (◘ Table 35.3) and local or regional anaesthesia, which is still rarely used in the prehospital setting in some countries.

There are various ways to successfully administer potent analgesics without establishing intravenous access. Examples include the intranasal administration of fentanyl, ketamine or nalbuphine (Pietsch et al. 2021, 2023; Egger et al. 2022). In the winter alpine environment, intranasal administration may result in an analgesic profile that differs from what rescuers in urban or clinical settings are accustomed to, due to altered pharmacokinetics. Delayed onset of action or even reduced efficacy may occur as a result of vasoconstriction of the nasal vessels or nasal congestion with secretions, both induced by cold. The also partially established enteral administration of analgesics by mouth is generally slow and plays a minor role in initial emergency care. Volatile analgesics such as methoxyflurane (Penthrox) are widely used in Australia and are now



◘ **Fig. 35.1** The Numerical Rating Scale (NRS) **a** and Visual Analogue Scale (VAS) **b** can be used to quantify and monitor the progression of pain

Table 35.1 Types of limb splinting

	Advantages	Disadvantages	Indications
Inflatable splint	Lightweight	Pressure on the limb may cause tissue damage. Technical failure possible. Pressure depends on altitude and external temperature	Rarely recommended in organised rescue
Mouldable splint, e.g. SAM®	Lightweight, compact, flexible. Technical failure almost excluded	Multiple parts may be required for the lower limb. Limited longitudinal stability	Suitable for most limb fractures
Improvised splint	Countless options, depending on the creativity of the rescuers and available materials, e.g. use of camping mats, sticks and adhesive tape	More time-consuming and less efficient than professional splinting materials	Maybe the best solution for companion rescue
Box or trough-like splint	Effective when the limb is positioned against the trunk. Splinting material is almost indestructible	Bulky to carry. Poor splinting if the limb is not aligned or is severely swollen	Suitable for non-displaced lower leg, knee and forearm fractures
Vacuum splint	Conforms to the limb. Easily moulded	Low risk of tissue damage. Bulky, technical failure possible. Stability depends on altitude and external temperature. Air pump required	Suitable for most limb and trunk fractures

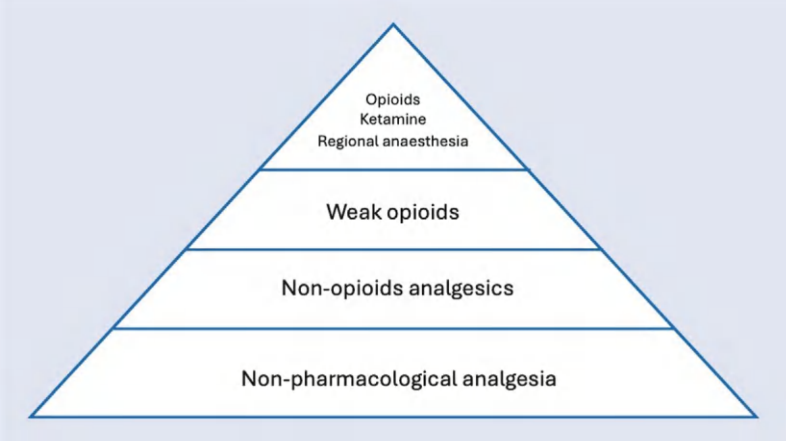


Fig. 35.2 Stepwise approach to pain management in alpine environments. Recommendations for specific pharmacological agents and dosages can be found in Table 35.3

Table 35.2 Advantages of non-pharmacological analgesia

Non-pharmacological pain reduction—Advantages
Reduction of blood loss
Prevention of neurovascular complications
Decreased risk of fat embolism
Decreased risk of further soft tissue injury
Facilitates evacuation

Adapted from Lee and Porter (2005)

increasingly found in the European alpine environment. Advantages include immediate availability and administration without the need for intravenous access.

Environmental conditions often play a crucial role in alpine emergency medicine, and it is important to minimise time spent on scene. The use of transmucosal fentanyl citrate (OTFC/Actiq® lozenge) was identified early on in the military as a possibility to meet this need and has been used by the military since the 1990s, where it is now the analgesic of first choice (Woolley et al. 2017).

Table 35.3 Selection of analgesics that can be used for the treatment of moderate to severe pain

Substance	**Route of administration**	**Initial dose**[a]	**Repeat dose**[a]	**Notes, contraindications (CI)**
Opioid				
Morphine	i.v.	5–10 mg (100 µg/kg, maximum 10 mg)	5 mg	CI in renal insufficiency
	i.m.	10–20 mg[a] (200 mcg/kg, maximum 10 mg)	10 mg	See above
	i.o.	5–10 mg[a] (100 mcg/kg, maximum 20 mg)	5 mg	See above
Fentanyl	i.v.	50–100 µg[a] (1–3 µg/kg, maximum 200 µg)	25 µg	CI with concomitant use of monoamine oxidase (MAO) inhibitors
	i.n.	180 µg[a] (1.5 µg/kg)	60 µg × 2 (15 µg × 2)	See above
	Buccal	OTFC/Actiq® lozenge 400–800 µg[a] (10–15 µg/kg)	–	See above
Tramadol	i.v.	50–100 mg (700 µg/kg) over 2–3 min	50 mg every 20 min; maximum 600 mg/day	CI with concomitant use of monoamine oxidase (MAO) inhibitors

(continued)

Table 35.3 (continued)

Substance	Route of administration	Initial dose[a]	Repeat dose[a]	Notes, contraindications (CI)
NSAID				
Ibuprofen	p.o.	400–800 mg	3–6 times daily (maximum 1200–2400 mg/day)	Risk of gastrointestinal ulcers and bleeding
Other				
Ketamine (for analgesia) half the dose for S-ketamine	i.v.	10–20 mg[a] (15–30 µg/kg)	5–20 mg	Co-administration of midazolam (1–3 mg i.v.) is recommended to prevent agitation and nightmares
	i.m.	1 mg/kg[a]	–	See above
	i.n.	0.5 mg/kg[a]	0.5 mg/kg	See above
Paracetamol	i.v.	>50 kg: 1 g; <50 kg: 15 mg/kg over 15 min	Dose may be repeated after 4–6 h	100-ml infusion over 15 min
Metamizole	i.v.	500–1000 mg (10–15 mg/kg)	Dose may be repeated after 4–6 h (maximum 5 g/day)	100-ml short infusion over 20 min (risk of hypotension if administered too rapidly)
Methoxyflurane (Penthrox 99.9%)	Inhaled	3 ml	A second 3-ml vial may be administered to prolong the duration of pain relief, but should only be used if necessary	Inhaled; applicator assembled as needed not suitable for use in enclosed spaces (e.g. helicopter cabin) caution: May induce malignant hyperthermia!

Expanded and modified after Ellerton et al. (2014)

OTFC oral, transmucosal fentanyl citrate

[a]Dosages apply to adult patients. For elderly, frail or haemodynamically unstable patients, dose reduction by half should be considered

The OTFC/Actiq® lozenge or Penthrox can be administered to the patient as soon as the rescue team arrives on scene, regardless of whether the team member is a first responder, paramedic or physician. This enables teams to provide a potent analgesic immediately without intravenous access. This represents a significant time advantage in hazardous, resource-limited environments such as remote alpine areas, where cold, snow and the risk of avalanches or rockfall may be present. The use of effective, non-intravenous analgesia can facilitate even faster evacuation without further delay.

The following section presents various techniques to enable readers to expand their expertise. In addition to theoretical instruction, practical training is of particular importance, as potent analgesics can have significant side effects that may lead to critical situations, especially in alpine terrain. Due to the often very remote geographical locations, climatic influences and long transport distances, an individualised approach is essential to ensure effective and, above all, patient-safe analgesia.

> There is no perfect analgesic for all situations. The use of different analgesics tailored to the specific situation is advisable. The number of analgesics carried should be reduced to the necessary minimum. Analgesics that can be administered via various routes and have a wide therapeutic range should be preferred. In addition, analgesics that allow for simple preparation and administration should be prioritised. They should be robustly packaged, and both the medication and its packaging must withstand alpine environmental conditions. Multimodal analgesia may offer advantages over single-agent analgesia.

35.1 Non-pharmacological Analgesia

Non-pharmacological analgesia can be provided by laypersons and non-physician rescue personnel. The analgesic effect is considerable, and potential side effects are minimal.

Stabilisation of the torso by pain-free positioning on an appropriate stretcher is mandatory for any injury to the torso or spine. In cases of limb fractures, the primary objective of non-pharmacological analgesia is splinting and immobilisation to stabilise the fracture site, thereby reducing pain and minimising soft tissue damage. ◘ Table 35.1 presents the various technical aids available for limb splinting, their advantages and disadvantages, as well as their respective indications. Special splinting systems, such as cervical collars and pelvic binders, and the prevention of adverse effects are discussed in ► Chap. 26.

Non-pharmacological analgesia may also be supported by effective protection against cold to prevent shivering (see ► Chap. 29) and by psychological support measures (e.g. empathy, conveying calm and reassurance).

The benefits of non-pharmacological analgesia through reduction and immobilisation of a fracture are listed in ◘ Table 35.2.

35.2 Pharmacological Analgesia

In principle, pharmacological analgesia should only be used as an adjunct to non-pharmacological pain management. The strategy for pain management should be as simple and safe as possible, particularly when the overall situation is complex (e.g. weather conditions, terrain, duration of evacuation, patient comorbidities), as any complications arising from initiated pain therapy must remain manageable. Mountain environments are unsuitable for therapies with unpredictable side effects that cannot be controlled. They are also not appropriate settings in which to trial pharmacological analgesia for the first time. For these reasons, a strategy should be chosen that is tried and tested and familiar to the rescuer. Patient-controlled analgesia, such as with Penthrox or OTFC/Actiq® lozenges, may offer advantages in this context.

When administered by non-medical personnel or in mass casualty incidents involving patients with moderate to severe pain, the use of easily administered analgesics—i.e. those not dependent on intravenous routes—may play a greater role in the future, for example, inhaled methoxyflurane, inhaled or intranasal ketamine, intranasal or transmucosal fentanyl or sublingual sufentanil (Carenzo et al. 2022; Lynch et al. 2022; Trimmel et al. 2022; De Valence and Suppan 2023; Dubecq et al. 2023; Patrick et al.

2023). Changes in legislation and guidelines could enable broader use by non-medical healthcare personnel, thereby improving prehospital analgesia (Vilcane et al. 2023).

35.2.1 Systemic Analgesia

Various agents are suitable for prehospital systemic analgesia in mountain environments. The choice of analgesic should be guided primarily by the experience of the provider. Preference should be given to medications with which the provider is thoroughly familiar. External factors such as cold, wind, sunlight and the time the patient remains recumbent can influence the pharmacodynamic and pharmacokinetic properties of many drugs, such as fentanyl, morphine, ketamine and midazolam (Kupper et al. 2006; van den Broek et al. 2010; Pietsch et al. 2022). These factors are often complex and not yet fully understood, so a high level of user expertise is advantageous for the safe administration of these substances.

A pain scale (e.g. VAS; ◘ Fig. 35.1) should be used whenever possible, as it allows for the initial assessment of the indication for analgesia in conscious patients and for monitoring the effectiveness of the initiated therapy. Medications with a rapid onset of action and a wide therapeutic window should be preferred whenever possible.

35.2.1.1 Principles of Systemic Pain Management

There is no perfect analgesic for prehospital use in mountain environments. For moderate to severe pain, the titrated administration of an opioid (e.g. fentanyl, morphine) or ketamine (e.g. in combination with midazolam) is recommended by numerous authors (Ellerton et al. 2014; Smith et al. 2009). In cases of less severe pain or in the absence of experience with the aforementioned substances, weak opioids (e.g. tramadol) and non-steroidal anti-inflammatory drugs (NSAIDs, e.g. diclofenac, ibuprofen), as well as centrally acting analgesics such as metamizole and paracetamol, represent a reasonable alternative (Cepeda et al. 2005; Craig et al. 2012). These medications can be administered individually, although the combination of two substances as part of a multimodal pain management approach offers analgesic advantages over monotherapy for numerous injury patterns and conditions (Russell et al. 2014). The recommended dosages of individual analgesics can be found in ◘ Table 35.3. ◘ Figure 35.2 presents a stepwise scheme for the recommended pharmacological pain management.

35.2.1.2 Opioids and Ketamine

The use of fentanyl and morphine in alpine environments presents a challenge, as both substances are associated with a range of clinically relevant side effects (e.g. respiratory depression, vomiting, nausea). Nevertheless, these agents play a central role in the management of moderate to severe pain. Compared to intravenous administration, substances that can be given buccally or nasally offer the advantage of being easier to store, transport and administer. Buccal and nasal administration is technically simpler than intravenous application and can be particularly beneficial in patients with difficult venous access. However, facial injuries and cold temperatures can significantly reduce the bioavailability of substances administered nasally or buccally. Under controlled conditions, for example, the bioavailability of intranasal fentanyl is approximately 71% compared to intravenous administration, meaning that the intranasal dose must be about 1.4 times higher to achieve a comparable effect (Borland et al. 2007). Prehospital administration of OTFC (Actiq® lozenge) in alpine settings has proven to be safe, simple and effective for various types of injuries, rescue methods and transport in all age groups and genders (Pietsch et al. 2023). In the context of use by Swiss ski and mountain rescue services, no relevant side effects requiring treatment were observed. Patient-controlled administration (sucking on the Actiq® lozenge) represents a valuable alternative for achieving rapid onset and easy administration without the delay associated with establishing intravenous access, especially in remote areas.

Ketamine induces dissociative anaesthesia and can be used for moderate to severe pain. The therapeutic range of ketamine is broader than that of opioids; however, the differing analgesic effects of racemic ketamine and the approximately twice as potent S-enantiomer (S-ketamine) must be considered (◘ Table 35.3). It is usually combined with a benzodiazepine (e.g. midazolam 1–3 mg), as monotherapy can occasionally lead to agitation and nightmares. Combination with an opioid is also possible to enhance the analgesic effect. With correct dosing, spontaneous breathing is maintained. As ketamine activates the sympathetic nervous system (e.g. increased heart rate and blood pressure), it is particularly suitable in cases of haemodynamic instability. Successful use has been reported at altitudes up to 4243 m (Grocott and Johannson 2007). Ketamine can be administered intravenously, intramuscularly, orally, sublingually, intranasally and rectally (◘ Table 35.3) (Russell et al. 2014). Low-dose administration of S-ketamine (0.125 mg/kg body weight) with 1 mg midazolam was associated with few and minor side effects and very high patient satisfaction in a mixed prehospital emergency medical system staffed by emergency physicians or paramedics according to German training standards (Häske et al. 2023). In children and adolescents, the use of ketamine and opioids is associated with high efficacy and few cases requiring ventilation (in the Frawley study, 6 indications for ventilation among 9033 cases involving opioid use) (Abebe et al. 2021; Frawley et al. 2023). In a nationwide Austrian study on analgesia in air rescue, opioids were used in 20,051 patients and S-ketamine in 9082 patients. In over 95% of cases, analgesia was adequate. Women were more likely than men to experience severe pain upon hospital arrival (5.0% vs. 3.2%). The safety of the analgesics was rated as high by the authors. Ventilation was required in 45 patients (0.2%), although the authors did not specify the causes, i.e. underlying disease or injury could also have contributed to the need for mechanical ventilation (Rugg et al. 2021). In a Swiss study conducted by the air rescue service Air-Glaciers, most emergency physicians used a combination of fentanyl with midazolam and ketamine. The median dose of midazolam was 2 mg, and the ketamine dose ranged from 0.2 to 0.7 mg/kg i.v. Psychomimetic events were rarely reported. Analgesia was described as safe and effective (Vanolli et al. 2020). The co-administration of ketamine and opioids may offer advantages in terms of analgesic efficacy and safety (Bansal et al. 2020). Titration of ketamine and opioids is recommended.

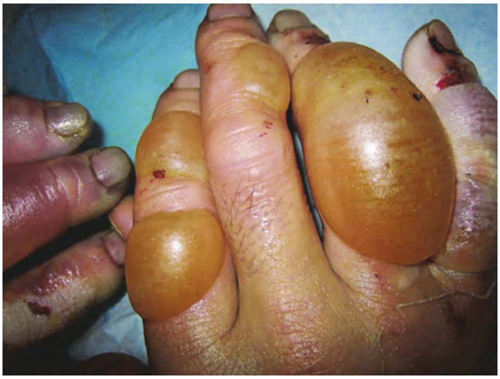
35.2.1.3 Non-opioid Analgesics

Non-opioid analgesics (NSAIDs as well as metamizole and paracetamol) have fewer side effects than opioids and ketamine and are also useful in the management of acute pain, although they are less effective. The use of non-opioid analgesics can, for example, reduce the required morphine dose by approximately 20% with paracetamol (Remy et al. 2005) and by up to 50% with ketorolac (Cepeda et al. 2005). In alpine environments, these analgesics are the first-line agents for mild to moderate pain (◘ Fig. 35.2) (Russell et al. 2014). To enhance their analgesic effect, it is advisable to combine two non-opioid analgesics (e.g. NSAID plus paracetamol or metamizole). Most non-opioid analgesics can be administered both orally and intravenously. When used short-term, side effects are minimal. With prolonged use over several days, the risk of liver damage (with paracetamol) or kidney injury and gastric ulcers (with NSAIDs) must be considered. NSAIDs generally cause a reversible inhibition of platelet function. There are limited data on the extent to which NSAIDs increase the risk of bleeding after trauma (Russell et al. 2014). However, data from the surgical literature suggest that short-term use of NSAIDs does not increase the risk of bleeding after trauma (Forrest et al. 1997; Lewis et al. 2013).

35.2.2 Local and Regional Anaesthesia

Over the past 15 years, regional anaesthesia has experienced significant growth in prehospital emergency medicine, first in French-speaking countries, then in English-speaking regions, and to some extent also in German-speaking areas. Especially when transport times to the hospital are prolonged, e.g. >>1 h, regional anaesthesia may be appropriate if the necessary technical resources and team expertise are available on site. For example, an Australian study involving 24 patients with femoral fractures demonstrated that a fascia iliaca block (FIB) performed by paramedics resulted in greater pain reduction than administration of morphine alone (reduction on an 11-point pain scale by 5 vs. 2 points after 15 min). On-scene time was comparable in both groups, and no side effects were observed in the FIB group (McRae et al. 2015). In a similarly designed study in the Netherlands, FIB was performed by ambulance nurses in 100 patients. FIB was effective in 96 patients and led to a reduction in pain on a 10-point scale from 6 to 3 within 30 min. No side effects were observed, and patient satisfaction was very high (Dochez et al. 2014). Successful prehospital use of an Oberst block by a paramedic has also been reported (Simpson et al. 2012). Furthermore, successful prehospital application of a sciatic nerve block by emergency physicians was reported in 20 out of 21 patients in France. The authors of this study concluded that prehospital sciatic nerve block provides effective analgesia. When performing nerve blocks, the use of a nerve stimulator increases accuracy and should therefore be preferred over anatomical landmarks alone (Gros et al. 2010). The use of ultrasound devices, now established in some prehospital systems, can further accelerate the performance of targeted regional anaesthesia and improve both patient comfort and success rates compared to nerve stimulation alone (Brookes et al. 2015; Lewis et al. 2015). The successful use of an interscalene block by an anaesthetist in France has been reported (Lagrabette et al. 2008), as well as a nerve block at the wrist (i.e. ulnar, median and radial nerves) performed by an emergency physician in Switzerland (Pasquier et al. 2012) (◘ Fig. 35.3). In cases of blunt thoracic trauma, a serratus anterior plane block may be considered (Harrington et al. 2022). According to a systematic review and meta-analysis, for proximal femoral fractures, a fascia iliaca compartment block provides better analgesia at low risk compared to a combination of oral or intravenous sedatives and opioids (Slade et al. 2023).

❯ Regional anaesthesia, when performed by experienced rescuers, can be a valuable alternative to systemic analgesia, espe-



◘ **Fig. 35.3** Superficial frostbite (grade II) of both hands, 24 h after the initial cold injury. (From Pasquier et al. 2012, with kind permission of Greg Zen Ruffinen) cially during prolonged transport. The prehospital use of ultrasound to facilitate regional anaesthesia is recommended.

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Terrestrial Mountain Rescue: Specific Medical Deployment Tactics

Fidel Elsensohn and Alexander Egger

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36.1 Special Operational Conditions

For ground-based emergency physicians, the overall situation during a mountain rescue operation differs significantly from the familiar scenarios in lowland or urban areas. The availability of Emergency Medical Helicopters in the mountains may leave the ground-based teams predominantly deployed in poor weather conditions or at night. Extended response times, the physical demands of reaching the scene and often the prolonged evacuations require a different situation-adapted medical management of the incident compared with a HEMS operation.

While the air rescue physician arrives at the scene fit, dry and warm, the ground-based emergency physician often arrives exhausted, sweaty and frequently soaked. In addition, the patient's condition has often deteriorated due to the extended injury-to-arrival time. All these factors complicate the initial assessment and diagnosis.

Patient monitoring is usually limited; monitoring devices are expensive, relatively fragile and not always available. Although small monitors exist, weather conditions or the patient's condition—such as hypothermia—often restrict continuous monitoring (Brown et al. 2012).

Casualties and patients in the mountain environment are considered hypothermic until proven otherwise. Medical interventions should not contribute to further cooling (Søreide 2014). Despite intensive training, the mountain emergency physician is regularly confronted with the situation that their helpers do not have the same high level of medical training as is the case in urban emergency systems, where dedicated staff usually assist the emergency physician. Tasks that can otherwise be delegated must be performed by the physician themselves. Nevertheless, they must not lose sight of the overall situation. Furthermore, they should not expose the patient, themselves or other rescuers to unnecessary risks by delaying evacuation with excessive medical interventions ('stay and play').

36.1.1 Medical Strategy in a Mountain Emergency Situation

The medical strategy during a mountain rescue operation depends on the following factors:

- *Maximum possible safety for rescuers and casualties:* The principles of comprehensive risk assessment take the highest priority.
- *Timeline*: Delayed alerting and prolonged response and transport times are key factors in the overall strategy for optimal treatment. On the one hand, a hazardous rescue may be avoided if, for example, a lifeless patient is found and, according to the criteria of the International Commission for Alpine Emergency Medicine (ICAR MEDCOM), resuscitation is not indicated (Lugnet et al. 2023). On the other hand, it may sometimes be advisable for the casualty to remain in a safe location if immediate medical intervention is not required or can be provided by companions.
- *Weather conditions*: Assessing the local weather situation and considering the time of day are essential prerequisites for a successful rescue operation. Here too, a balance must be struck between rapid evacuation and transport with minimal care versus comprehensive treatment in accordance with international guidelines. After nightfall, there is a significant increased risk for both rescuers and casualties; a rescue may even become impossible.
- *Minimal care* versus *maximal care*: This decision requires considerable experience on the part of the mountain emer-

gency physician. A maximal, guideline-based strategy is not always possible or indicated. The principle of optimal care applies, and this must take into account the overall situation of the operation. Furthermore, available resources are often insufficient for a prolonged transport and, if needed, can only be supplemented with significant delay, if at all.

- *Limits of treatment*: 'Not everything that is possible is appropriate in a given situation.' Futile treatment attempts in the absence of routine or unrecognised injury patterns pose significant risks to the casualty. Pre-existing conditions and prior medication are often unknown. Drug interactions or allergic reactions can turn a manageable situation into a catastrophe. In incidents involving multiple casualties, triage may be indicated.
- *Transport route and method*: Whenever possible, helicopter transport will be preferred. In conditions where air rescue is not feasible, a safe and as rapid as possible terrestrial transport must be arranged. From the outset of medical care, consideration as to whether the initiated treatment can be continued seamlessly under the expected future circumstances until the casualty reaches definitive care. Coordination between the emergency physician, the incident commander and the on-site team leader is essential. To ensure the fastest possible evacuation, a decision must be made immediately after the initial medical assessment on the mode of transport. The expected technical requirements and plans must be implemented as quickly as possible and appropriate back-up options considered if the plan changes.

36.1.2 Risk Management by the Emergency Physician in Mountain Rescue Operations

Although risk management in mountain rescue operations predominantly lies with the on-site incident commander, every rescuer, regardless of their role, is part of the risk management process. This applies especially to the mountain emergency physician, as their assessment of the situation not only relates to objective hazards but also influences their clinical decisions. The purpose of risk management is to continually identify existing risks, assess them and take action to reduce harm. Thereby, the overall risk is reduced and control of the situation increased. For the mountain emergency physician, this means determining the immediately necessary medical interventions through the most accurate initial assessment possible. From this, a strategy for evacuation, transport with the necessary or available rescue resources and an appropriate destination hospital must be established in consultation with the on-site incident commander and the overall operations manager. The emergency physician must anticipate potential deterioration in the patient's condition and address possible interventions. These possibilities and uncertainties must be discussed with the rescue team, especially the immediate medical assistants, and the necessary steps must be defined in a structured manner. Information provided to the rescue team and incident command should be as up-to-date and limited to the immediately necessary details as possible. Communication with the control centre should, if possible, be conducted directly by the emergency physician, as this allows any queries to be answered without delay. A dedicated radio channel or direct call via the mobile network is required for data protection reasons. Accurate assessment of human factors in risk evaluation, the situation, on-site measures, and transport can help prevent overload and exhaustion. Especially during prolonged, physically demanding, and psychologically traumatic operations, diminishing physical and mental strength can lead to misjudgements and errors. Risk management also means taking appropriate measures to minimise risk without delaying evacuation and transport and ensuring that necessary medical interventions are carried out. The risk management process begins with the identification of possible objective risks in conjunction with those arising from attempted and/or initiated medical interventions. Mention should be made of delays in rescue due to anaesthesia and endotracheal intubation and analgesia-associated sedation with the resultant complex evacuation requirements. After risk assessment, the available options must be decided upon. The more severe or even life-threatening an injury or illness is, the higher the risk that is usually accepted. In such cases, a rapid and comprehensive analysis of the situation by the entire rescue team is essential. This enables a team decision to be implemented as effectively and consensually as possible. The identified risk must also be continuously reassessed. Once initiated, therapy should be continued until handover is possible. Any subsequent delivery of medical or technical equipment may delay the entire rescue operation. It may also be necessary, if the patient's condition changes, to promptly initiate the required measures and coordinate the new operational strategy with the incident commander. In extreme weather conditions, it may even be advisable to remain with a stable patient at a safe location (e.g. hut or bivouac) until conditions allow for a safer terrestrial or, possibly, an air evacuation. There are also situations in which the emergency physician is only called in retrospectively, either because no doctor was available from the outset or because the initial incident report did not accurately reflect the severity of the injuries or illnesses. In such cases, the question arises: Can the patient be stabilised and transported by first responders to meet the incoming physician, or must the emergency doctor ascend to the accident site? Via radio or mobile phone, symptoms and the severity of injuries can often be sufficiently assessed to initiate the first therapeutic steps. This can expedite an operation that would otherwise have taken much longer (◘ Fig. 36.1).

In principle:

> Do not accept a high risk for a small benefit: 'Evaluate risk versus gain.'

For example:

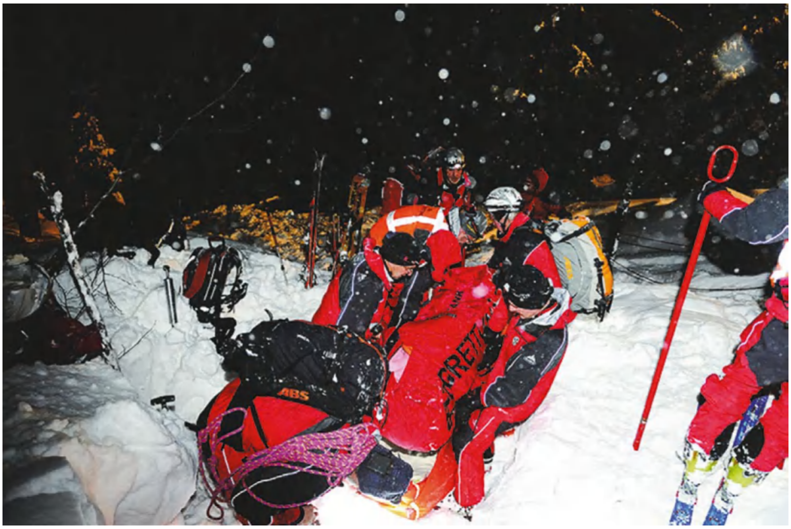
- If the patient is in a safe location with adequate equipment, use that benefit for a good outcome.
- Cases of minor injuries and mild illnesses can be managed by companions,
- In poor weather conditions with a hazardous approach (e.g. avalanche risk) or at high altitude (e.g. if rescuers are not acclimatised), consider significant deviations from the 'norm'.
- In the absence of technical equipment (e.g. no radio coverage), have back-up plans agreed before it's too late.

> A routine operation is not synonymous with a low-risk operation.

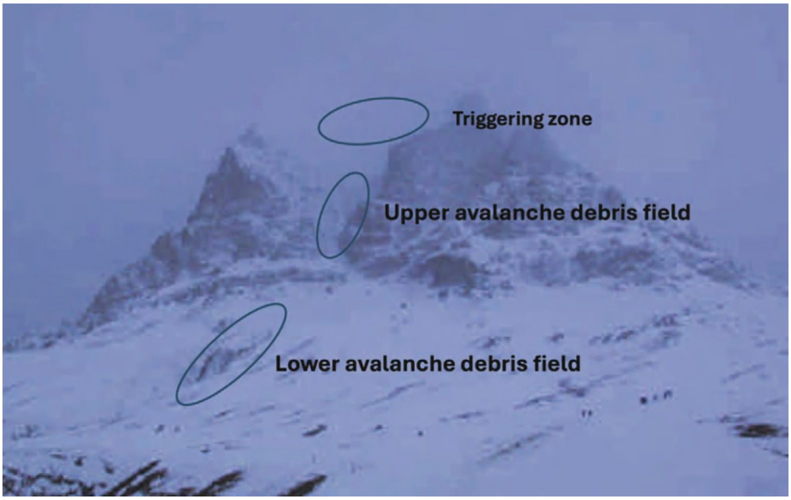
36.1.2.1 Case Study

Avalanche Incident at Widderstein, Vorarlberg, Midwinter

Imagine: A large avalanche is observed from a nearby ski area, and an avalanche rescue operation is immediately initiated via the control centre (◘ Fig. 36.2). The first emergency medical helicopter arrives at the accident site 5 min later, followed by another and then a third helicopter from the mountain police within 25 min of the avalanche. The operational area



■ **Fig. 36.1** Winter operation at night. (Image rights: F. Elsensohn)



■ **Fig. 36.2** **a, b** Widderstein avalanche. (Image rights: F. Elsensohn)

is affected by poor weather with fog and snowfall, and the summit is shrouded in clouds (■ Fig. 36.2). During the initial flyover, two avalanche debris fields are identified, and a person is sighted on the upper one. Despite the ongoing high avalanche risk, this person is picked up by the first helicopter and flown to the incident command base. The individual is only minimally injured and describes the situation: three mountaineers were undertaking a winter ascent as training for a Himalayan expedition. They were caught by a slab avalanche below the summit ridge and carried several hundred metres. The rescued person reports large snow masses are still present in the summit area.

The rescue team is faced with the following situation: two buried persons, without avalanche airbags but with avalanche transceivers, unclear where they are buried, very high risk of secondary avalanches, hazardous ascent and an avalanche path with high rock steps and a deposition zone in a ravine.

The relatives of the buried persons exert significant pressure on the rescue teams, especially on the incident commander and the emergency physician, to commence the search immediately. If not, the relatives would attempt a rescue themselves. The mountain police on site eventually succeeded in dissuading the relatives from such an undertaking.

The emergency physician is confronted with the following questions:

- What is the probability of survival for the buried persons?
- How does the risk compare to the potential benefit?

Risk: Due to the very high risk of secondary avalanches, no rescue teams are sent into the deposition zones; a Recco (▶ https://recco.com) flight and transport flights cannot be carried out as fog increases.

Benefit: The likelihood that the victims can be rescued within a timeframe that would make survival probable is minimal.

Decision: The benefit of immediate search is disproportionate to the potential risk to the rescue teams.

After an improvement in the weather the following day, a controlled triggering of the snow pack by helicopter using explosives is carried out in the summit area, releasing very large masses of snow.

After 2 days of searching, the victims were eventually recovered from the lower avalanche debris under 8 metres of snow. Post-mortem examination reveals that both died from injuries that led directly to death.

Conclusion: Despite immediate alerting and the prompt availability of sufficient rescue personnel, the rescue of the avalanche victims had to be postponed until conditions allowed for a sufficiently safe operation. The decision regarding the probability of survival posed significant challenges for the technical and medical incident command. The considerable pressure from relatives and the media represented an additional challenge.

36.2 Trauma Management

Most mountain rescue operations are due to injuries. The most important tasks of the emergency physician at the scene are:

- Consideration of the mechanism of injury to correctly assess the possible injury pattern,
- Thorough clinical examination of the casualty to identify all potentially life-threatening injuries,
- Appropriate analgesia,
- Stabilisation of impaired vital signs.

Above all, risk assessment is paramount—whether treatment can be provided immediately at the scene or whether the patient must first be evacuated from a danger zone (e.g. rockfall).To minimise risk for all involved, guideline-based therapy is not always possible during mountain rescue operations.

36.2.1 Pain Management

Often, the placement of an intravenous line for the administration of medication and infusions to stabilise circulation should be carried out. After careful assessment of pain intensity, a potent analgesic can be administered to enable pain-reduced positioning, reduction and splinting of fractures. The emergency physician should only administer analgesics with which they are thoroughly familiar regarding their effects and side effects.

The most commonly used and most suitable analgesics are potent opioids (e.g. fentanyl and piritramide) as well as ketamine in combination with a sedative (Smith et al. 2012; Ellerton et al. 2013). Opioid side effects such as respiratory depression and nausea must be recognised and managed promptly. Procedural sedation must always preserve protective reflexes; otherwise, airway management becomes necessary. Ketamine can cause 'bad dreams', which can be reduced by maintaining a quiet environment (e.g. minimising noise) and mild sedation (Ellerton et al. 2009a, Ellerton et al.2009b).

All potent analgesics should be administered against symptoms and titrated. However, there is no perfect analgesic for pre-hospital use in the mountains. The fact that increasing numbers of older people on long-term medication are seeking recreation in the mountains must be considered when selecting and dosing medication in emergency situations. Interactions and side effects must be given particular attention, especially when psychotropic substances are involved.

Hypothermia affects the pharmacokinetics and pharmacodynamics of all substances; therefore, analgesics should be administered in lower doses, and the potential sympathomimetic side effects of ketamine (cardiac arrhythmias) should be considered (Ellerton et al. 2014). As most adverse effects occur within the first 30 min, in cases of suspected risk, a difficult transport with limited patient monitoring should, if possible, be postponed (Newman et al. 2003).

For situations in which intravenous administration of analgesics is not possible, alternative routes are available: opioids, ketamine and midazolam can be administered intranasally. Special syringe attachments are used for this purpose (e.g. MAD®, Mucosal Atomisation Device). The effect and onset of action are like intravenous administration (Castner 2005). Inhalational forms of pain management such as methoxyflurane (Penthrox®) and the nitrous oxide-oxygen mixture (Livopan®) have also been in use in Central Europe for some time. While the nitrous oxide-oxygen mixture has only proven to be of moderate value for mountain emergency use (and its weight is high), methoxyflurane (Penthrox®) is more widely used in mountain rescue services. Owing to the substance's favourable side-effect profile, it can be considered safe for non-medical users to administer provided the legal framework of the respective country allows it (Egger et al. 2022). The buccal route of administration is also available (e.g. fentanyl lollipop, Buccalam®); there are, as yet, no valid data from the context of mountain emergency medicine. However, it is already being used in part at helicopter bases.

> Adequate pain management at the scene of an accident in the mountains is a human right. (U. Wiget in Elsensohn 2002, p. 134).

36.2.2 Fluid Therapy

Patients with injuries involving severe bleeding, such as in traumatic brain injury (TBI) or multiple trauma, require a differentiated medical approach. There are various therapeutic protocols for fluid replacement therapy in multiple trauma with impending hypovolaemic shock. Accurate assessment of injury severity and circulatory status is often difficult in mountain rescue operations (Sumann et al. 2009, 2020).

Prehospital shock management is guided by the question of whether there is severe internal or external bleeding that cannot be controlled with available resources, or whether the primary injury is a traumatic brain injury. In cases of severe internal bleeding (injuries to major vessels, liver or splenic rupture), immediate transport to the nearest appropriate hospital should be prioritised, as any time-consuming therapy worsens the outcome.

> Rapid evacuation can be an important therapeutic option.

In such cases, it is recommended to accept mild hypotension with a systolic blood pressure of <90 mmHg (i.e. permissive hypotension). Aggressive fluid management leads to hypothermia and a coagulopathy, thereby exacerbating bleeding. In the presence of traumatic brain injury (TBI), however, rapid

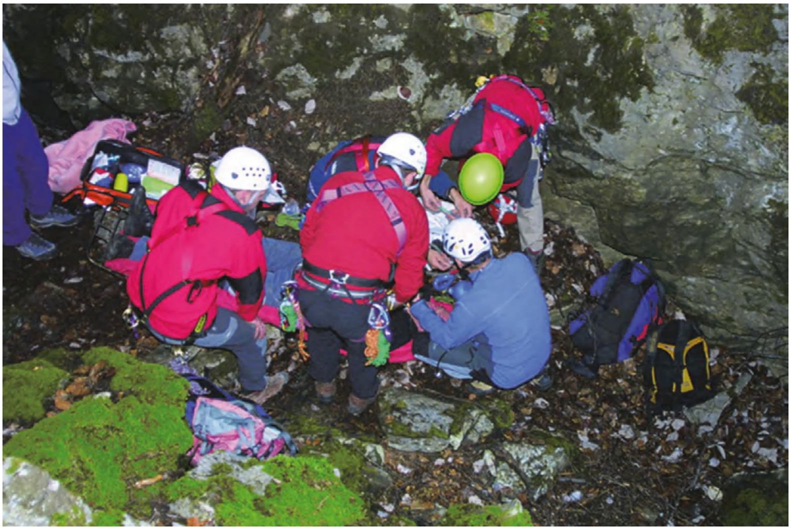


Fig. 36.3 Trauma care in the field. (Image rights: F. Elsensohn)

stabilisation of circulation with systolic blood pressure values >110 mmHg should be aimed for (Sumann et al. 2020).

In addition to pharmacological therapy, prompt and appropriate realignment of fractures and dislocations is essential for pain relief and haemostasis. In mountain rescue, splints, vacuum splints and vacuum mattresses are used for this purpose (Ellerton et al. 2009a, b). Alongside these measures, effective thermal insulation using aluminium rescue blankets and heat packs is of great importance, as hypothermia dramatically worsens the outcome for trauma patients (Søreide 2014).

In summary, the management of patients with severe injuries in mountainous terrain under austere conditions represents a major challenge for the mountain emergency physician. Rapid assessment of injury severity, optimal pain and fluid therapy, and the aim of performing only what is necessary as quickly as possible are the cornerstones of the medical strategy. Figure 36.3 illustrates the emergency medical care of a fallen patient by the emergency physician and mountain rescuer under difficult conditions.

36.3 Specific Mountain Emergency Situations

36.3.1 Avalanche Accident

The tasks of the mountain emergency physician and the management of snow-buried persons are discussed in ▶ Chap. 31. In avalanche accidents, operational tactics are more the responsibility of the rescue organisation than of the emergency physician. It is crucial that the emergency physician is brought to the scene as quickly as possible (e.g. with the first emergency medical helicopter), to be present during the extrication of buried persons.

In the event of multiple burials, the first emergency physician coordinates the arriving rescue teams in cooperation with the on-site incident commander. The aim is to deploy available resources as effectively as possible to maximise the survival chances of as many buried persons as possible. If there are enough doctors on the avalanche field, one physician should, if possible, be directly involved in the rescue of buried persons. The findings obtained before extrication of the victim, such as air pocket, airway status, and vital signs, have major implications for subsequent medical decisions, but can be difficult to reconstruct later if not documented at the time.

The lead emergency physician on the avalanche debris must, in consultation with the rescue coordination centre, ensure that the transport of the buried persons is organised so the right person arrives at the appropriate target hospital. Every physician called to an avalanche accident must be thoroughly familiar with, and adhere to, the specific triage and treatment guidelines.

> ❯ No avalanche victim without obvious lethal injuries, and with a clear airway, should be considered dead until they have been rewarmed and are still dead (Pasquier et al. 2023).

36.3.2 Crevasse Fall

Falls into glacier crevasses usually result in a combination of life-threatening injuries and hypothermia. Severe soft tissue injuries caused by crampons, pelvic and spinal injuries, as well as fractures, are common. Rapid medical care is not possible if casualties are wedged deep within a crevasse and the technical rescue is difficult.

If adequate medical care cannot be provided in the crevasse, the physician may have to limit their intervention to giving analgesia. The technical rescue should be carried out as gently as possible. (Winterberger et al. 2008).

If the emergency physician is not lowered down to the patient, they can give instructions from the edge of the crevasse to the rescuers regarding immobilisation of the injured person, thereby preventing further harm. In such incidents, technical rescue often takes precedence over medical care.

36.3.3 Suspension from a Rope

Immobile suspension from a rope (‘suspension syndrome’) can lead to circulatory collapse due to pooling of blood in the lower body and, if prolonged, to death. Although the pathophysiological mechanism is not fully understood, for many years, the prevailing teaching was that the victim should be placed in a squatting or crouched position after rescue.

For a long time, horizontal positioning of the patient and fluid resuscitation were viewed critically, as it was feared that an acute overload of the circulation from the return of pooled blood could cause arrhythmias and cardiac arrest. More recent studies have refuted this theory for several reasons. Climbers who remain immobile hung on a rope for extended periods are usually healthy, physically active individuals who generally tolerate a temporary increase in cardiac volume well. Furthermore, data on causes of death and so-called rescue death after suspension on a rope are very limited (see ► Chap. 33).

A sitting position also does not consider potential severe internal injuries or spinal trauma. Patients with circulatory problems from other causes are generally treated in the supine position. Assessment of injuries and circulatory status in an unconscious, freely suspended patient can be very difficult. The therapeutic approach should therefore follow the general ALS (Advanced Life Support) protocol (Mortimer 2011; Thomassen et al. 2009; Rauch et al. 2019, 2023).

36.3.4 Medical Emergency

An increasing number of older individuals with pre-existing conditions seek recreation and physical challenge in the mountains, resulting in a higher incidence of acute medical emergencies in mountain environments. Acute coronary syndrome and myocardial infarction are common. In principle, the same medical treatment guidelines apply in the mountains as for medical emergencies in lowland or urban areas (see ▶ Sect. 21.3.1).

If a helicopter rescue is not possible, options are severely limited. In ground-based operations, small-sized monitors and treatment systems (such as compact semi-automatic defibrillators with a monitor) facilitate diagnosis and therapy even in cardiac or other emergencies. Automated chest compression devices such as CorpulsCPR® and LUCAS® enable continuous chest compressions during transport (Egger et al. 2022).

36.3.5 Search Operation

A search operation places minimal medical demands on the mountain emergency physician. However, if the missing persons are not found for an extended period, weather conditions deteriorate dramatically, and the risk to rescuers increases, the physician may be confronted with the question of the chance that the person will survive should the search be abandoned. This assessment depends largely on the available information. A collateral history regarding regular medication and physical fitness, as well as equipment and clothing, is of great importance.

36.3.6 Mass Casualty Incident

Mass casualty incidents in the mountains are rare and pose enormous challenges for rescue teams and the responsible authorities. Injuries that would normally be survivable can lead to death in the context of major incidents in mountainous terrain. Not all physicians and rescue teams involved have experience in managing major incidents, especially in mountainous terrain.

Senior emergency physicians qualified for disaster situations should be trained in mountain emergency medicine and prepared to manage such large-scale incidents in mountainous environments. Close cooperation with the incident command is essential. Furthermore, care must be taken to ensure that physicians and helpers inexperienced in mountain environments do not endanger themselves in the hectic course of events. The senior emergency physician will also be responsible for triage of the injured and the selection of destination hospitals.

36.3.7 Combined Ground and Air Rescue Operations

The use of emergency medical helicopters in mountainous areas has become indispensable. In suitable flying conditions, most HEMS missions are carried out without ground support. However, in complex technical operations, at night, or in poor weather, combined ground and air rescue missions are often necessary. In such cases, precise coordination among all attending physicians is essential. The ground-based physician must be familiar with the possibilities and risks of helicopter deployment, and conversely, the air rescue physician should be aware of the capabilities and limitations of the ground team. For this reason, it is necessary that both rescue systems not only work together during missions but also train together in advance (Tomazin and Kovacs 2003; Tomazin et al. 2011).

36.3.8 Aborting a Mission

The decision to abort a mission always lies within the authority of the incident commander. As a rule, the commander will consult the attending emergency physician to jointly assess survival chances as part of a risk evaluation. Fundamentally, the safety of the rescuers takes the highest priority.

If the survival chances of the missing person are considered high, it can be difficult to halt an operation. This situation frequently arises in avalanche accidents; avalanches are one of the leading causes of rescuer death. Such decisions are also common during search operations when the risk to search teams increases. The media can exert enormous pressure, and biased reporting is more the rule than the exception.

36.3.9 Confirmation of Death

Not only in avalanche operations does the question repeatedly arise as to whether, and if so, for how long resuscitation should be attempted. Legally, death must be confirmed by a physician. However, a physician is not always present when a lifeless person is found. Although triage criteria for completely buried avalanche victims are defined, studies show they are not always applied. If no physician is present at the scene, other criteria may be used. In cases of injuries incompatible with life, signs of decomposition, a body frozen solid and, above all, an unacceptable risk to rescuers, resuscitation may be renounced (Lugnet et al. 2023; Schön et al. 2020; Paal et al. 2011). Under special circumstances, remote consultation with a mountain rescue physician can also facilitate decision-making by rescuers on site.

36.4 Equipment

Should the mountain rescue physician equip themselves for all eventualities on a mission, or keep their equipment as minimal as possible, even at the risk of limiting treatment options? In principle, medical equipment should be as lightweight as possible and adapted to the expected scenario (Elsensohn et al. 2011). The mountain emergency physician should be familiar with the medications used, including their effects and side effects.

In extreme situations involving long and difficult approaches, it may be appropriate for the attending emergency physician to carry only enough equipment to provide appropriate analgesia, thereby enabling the rescue to humanely proceed to the next stage. The equipment of first responders on site should be replaceable when subsequent teams arrive (▣ Table 36.1).

▣ Table 36.1 Recommendation for the contents of an emergency physician's rucksack for mountain rescue operations

Application	Material/Medication	
Trauma	Splinting and immobilisation materials, scissors, surgical forceps, scalpel, sterile gloves, OP-site® film	(if not already included in the first responder's rucksack at the accident site)
Protection against cold	Protection against cold (aluminium emergency blankets), heat packs	
Infusions	2 × 500 ml crystalloid solution	4 intravenous cannulas, fixation material

(continued)

Table 36.1 (continued)

Application	**Material/Medication**	
Analgesics	Opioids, ketamine, possibly paracetamol, metamizole	Ketamine in combination with a sedative, possibly via MAD® (mucosal atomisation device)
Hypnotics	Midazolam, Propofol	
Muscle relaxants	Rocuronium	
Bronchodilators	Inhaled beta-agonists	
Other	Antiallergic agent, steroids (Methylprednisolone, Dexamethasone, Glucose 40%	
ALS	Adrenaline, Acetylsalicylic acid, Urapidil, Atropine, antiarrhythmics (Amiodarone), beta-blockers	Only if monitoring is possible (AED with ECG capability)
Ventilation	Ventilation bag with filter and 3 masks, laryngoscope with spare batteries, 2 blades, stylet, Magill forceps, cuff syringe, tube fixation, suction pump (manual), possibly alternative supraglottic airway devices (e.g. laryngeal mask)	Prefer plastic blades due to risk of freezing to the tongue in extreme cold, possibly oxygen, thoracotomy set and urine bag
Monitoring	Blood pressure measurement, pulse oximetry, capnometry, tympanic thermometer, blood glucose meter, stethoscope	Possibly AED with ECG capability
Miscellaneous	Headlamp (LED), scissors, foreign body forceps, high-visibility vest (emergency physician), patient transport bag with waterproof marker	Possibly personal equipment and hot drinks

ALS advanced life support, *AED* automated external defibrillator

Conclusion

Emergencies in mountain terrain place high demands on the medical expertise and physical fitness of the mountain emergency physician. In addition to sound knowledge of emergency medicine, the decision regarding the optimal operational strategy also requires experience in technical rescue. An emergency physician with no mountain experience may place the patient, themselves, and all other rescuers at significant risk. The mountain emergency physician must adapt their treatment strategy to the specific situation to transport the casualty to the most appropriate hospital as quickly and safely as possible.

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Requirements for Mountain Rescue Physicians and Mountain Air Rescue Physicians

Fidel Elsensohn, Guenther Sumann, and Alexander Egger

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Trailer

The rescue and care of casualties in difficult terrain and adverse weather conditions require specially equipped rescue organisations with qualified personnel. Topographical features and hazards such as rock or ice fall, avalanches and the risk of falling often limit the scope of medical interventions. Time constraints (such as approaching darkness and the associated increased risk) and the lack of professional support staff frequently add to the difficulty.

In addition, cold, wet conditions and altitude complicate initial care. Mountain emergency physicians must strive to meet modern standards of emergency medicine even under challenging circumstances. However, their own safety and that of other rescuers must never be compromised. This requires not only excellent emergency medical knowledge, but also advanced mountaineering and rescue technical skills.

37.1 General Requirements for Mountain Rescue Physicians

The mountain rescue physician is first and foremost a member of a mountain rescue team. They must know and trust their colleagues, and their colleagues must know and trust them. This is essential for efficient teamwork to be possible in extreme situations. Ideally, the mountain rescue physician also participates in the medical training of team members and personally conducts continuing education. Only through continual training and education can they assess the technical and medical skills of their team members and assign tasks according to their abilities during operations.

A complex task such as a terrestrial mountain rescue operation can only be accomplished as a team. It is often necessary for physicians from different rescue organisations (ambulance services or air rescue teams) to cooperate with local teams during joint missions. This places increased demands on the lead organisation in terms of communication and ensuring safety, as the mountaineering and logistical skills of these physicians may be unknown to them.

37.2 Specific Medical Requirements

The mountain rescue physician must hold a valid emergency medicine qualification in accordance with the training requirements of their respective country. Regular continuing education to maintain this qualification must be done as required. Obtaining an international mountain medicine diploma according to the guidelines of the International Society of Mountain Medicine (ISMM), International Commission for Alpine Rescue (ICAR) and Union Internationale des Associations d'Alpinisme (UIAA) is recommended: Diploma in Mountain Medicine (DIMM). The management of accidents or illnesses in mountainous terrain requires specialised knowledge of treatment, complications and transport. In mountain rescue practice, not all usually required medical interventions can always be performed at the scene. The mountain rescue physician must be able to rapidly and purposefully carry out essential and lifesaving interventions, such as airway management or pain control, prior to technical rescue.

This requires competence and experience. The emergency physician may endanger not only the health and life of the patient, but also that of their colleagues by carrying out unnecessary or non-vital interventions. Certain emergency situations such as avalanche accidents, hypothermia, canyoning incidents, crevasse falls, and mass casualty events require specific knowledge of medical management, specialised operational tactics and cooperation with

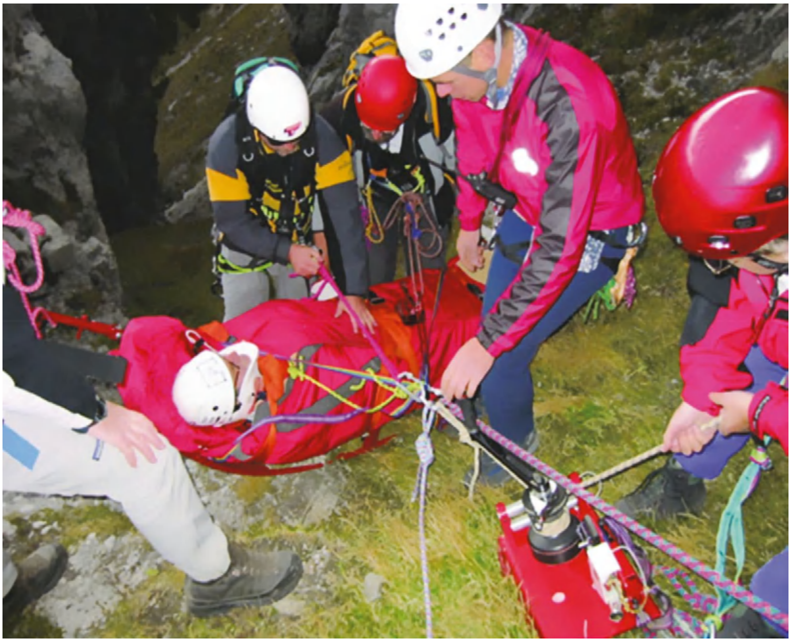

Fig. 37.1 Night-time rescue operation with extraction through a rocky gorge. (Image rights: Fidel Elsensohn)

other rescue organisations and control centres.

In addition, the mountain rescue physician must be familiar with the practical management of traumatic emergencies in mountainous terrain. Splinting and positioning of fractures, the occasional need for reduction of shoulder dislocations and ankle joint dislocation fractures, as well as the management of a polytraumatised casualty in the mountains, all require a solid foundation in trauma care (Sumann et al. 2020; Ellerton et al. 2009).

Figure 37.1 shows a rescue operation involving the extraction of a casualty through a rocky gorge

37.3 Equipment

The ongoing inspection of medical equipment and medications is an additional responsibility of the mountain rescue physician. Mountain rescue operations differ from those in inhabited areas not only because of the geography, but also because all equipment must be carried. A lightweight, appropriate distribution of medical supplies is essential. National and international recommendations regarding equipment standards need to be adapted to local conditions (Elsensohn et al. 2011).

37.4 Mountain, Physical and Technical Rescue Competence

Mountain rescue physicians must be able to move safely in the terrain in which they are deployed. Their endurance should enable them to ascend 400 vertical metres per hour with their equipment. A long, operational approach to the emergency site can be physically demanding. Recent studies show that this factor also affects the quality of care provided (Egger et al. 2020; Niederer et al. 2023). Appropriate physical fitness therefore has a positive impact.

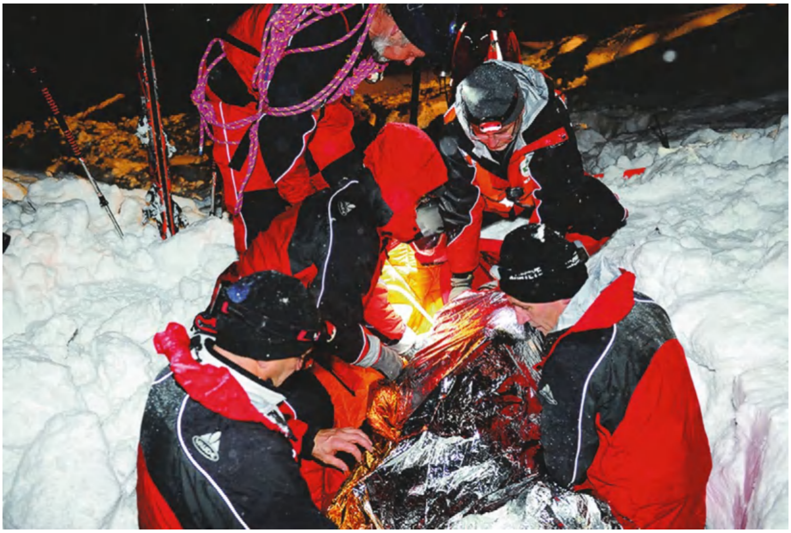

Fig. 37.2 Management of an injured mountaineer in the field. (Image rights: Fidel Elsensohn)

In terms of climbing skills, independent climbing at UIAA grade II is likely to be a minimum requirement, and with rope protection, grade III should be achievable.

As a member of a mountain rescue team, the physician is personally responsible for their own safety. Confident ascent and descent on skis in open terrain, as well as safe movement and climbing on ice, and basic knowledge of ice climbing are usually required. The mountain rescue physician must be familiar with and able to use the rescue equipment deployed.

The principle that the physician, whenever possible, reaches the patient and provides initial care at the accident site requires them to have a high level of mountain and technical rescue competence. Active and passive abseiling into difficult terrain, continual assessment of personal safety and the awareness that medical management must be adapted to the prevailing circumstances to minimise operational risk all place high demands on their medical and technical skills.

Belay construction and safety techniques, as well as technical and improvised rescue procedures, should be mastered. Knowledge of the use of avalanche transceivers, the rescue of buried persons and the guideline-compliant management of avalanche victims is essential. Basic orientation skills and proficiency with navigational aids should enable independent descent to the valley in special cases. The emergency physician in a mountain rescue team should be integrated into the command and logistics of the entire operation.

They must be familiar with the local emergency services and their capabilities to use them optimally. In stressful situations, the mountain rescue physician must demonstrate leadership skills; their medical assessment often has far-reaching consequences (Rammlmair et al. 2001). ◘ Figure 37.2 shows the emergency management of an injured mountaineer in the field.

37.5 Personal Competence

Personal competence and empathy for the situation of casualties, relatives and colleagues are often difficult to maintain in stressful situations. Through daily routine in dealing with patients, physicians sometimes lose sight of their own and others' psychological vulnerability when they are treating casualties.

The mountain rescue physician must also provide psychological support to casualties during often time-consuming operations. In addition, it is important to recognise the distress of relatives. In tourist regions, additional foreign language skills are therefore helpful. Furthermore, the mountain rescue physician must be able to identify the psychological strain on colleagues, especially after difficult missions or the recovery of fatalities, and should be able to assist with grief and stress management.

Debriefings and personal commitment are required; camaraderie demands both openness and confidentiality. A professional approach to the media is expected of the emergency physician and, in operations with a high degree of public interest, can represent a real challenge.

37.6 Environmental Requirements

The mountain rescue physician's place of residence should be as close as possible to their area of operation. This enables rapid deployment to the accident site. Regular participation in training and exercises as part of the local mountain rescue team is important. The willingness to work within a rescue organisation requires a high level of personal commitment.

Acquiring the necessary medical and technical skills is time-consuming and associated with a financial commitment. The work is generally voluntary, and after a long and exhausting operation, regular work often continues the following day.

37.7 Training Opportunities

There are not many courses available in mountain emergency medicine. In mountainous countries, national societies for mountain medicine provide the relevant postgraduate training with the DIMM, as well as additional modules for ongoing education and training (Peters and Plotz 1998).

37.8 Requirements for the Mountain Air Rescue Physician

The mountain air rescue physician should, in principle, meet the same mountaineering requirements as the mountain rescue physician operating terrestrially. The widespread presence of helicopter bases in the European Alps often makes it possible to transport severely injured patients to an appropriate destination hospital within the 'golden hour' (Marsigny et al. 1999; Scrimgeour 2003; Tomazin et al. 2011). To achieve these objectives, the air rescue physician must act quickly and prudently in accordance with international guidelines.

A thorough knowledge of trauma management as well as circulatory and airway management is essential. Air rescue physicians are often called to particularly severe cases or take over care of patients from primary care doctors and are frequently confronted with the need for additional competencies in anaesthetic procedures. The structure of medical care and the destination hospitals within the operational radius must be well understood in order to select the appropriate transport destination. Sometimes there are considerable operational and flight altitudes, so the air rescue physician must have sufficient basic knowledge of altitude and aviation physiology to assess relevant effects on the patient's condition and management.

Safety plays a major role in air rescue. The emergency physician is part of a helicopter crew that often consists of only three, sometimes four, members. It is essential that they can be relied upon to fulfil all safety-relevant requirements reliably, in addition to their demanding emergency medical and mountaineering duties. Accordingly, some air rescue operators conduct comprehensive selection procedures for air rescue physicians, in which, alongside the basic medical and mountaineering requirements, particular emphasis is placed on human factors, teamwork, resilience and reliability. The mountain air rescue physician must complete specific training and continuing education in accordance with the regulations of the respective air rescue operator.

Thanks to the use of air rescue in the mountains, spectacular rescues are possible, and even after the most severe injuries, casualties can sometimes survive situations that would otherwise be unsurvivable without air rescue. However, it is essential to rapidly recognise and correctly assess the limitations. This applies to both invasive emergency medical interventions and technical rescue operations.

37.9 NACA Score

The NACA score (NACA scale) is traditionally used in air rescue to describe the severity of injuries or illnesses. It was originally developed by the National Advisory Committee for Aeronautics with regard to aviation accidents. From NACA 4 onwards, the involvement of an emergency physician is required; in mountain air rescue in the Alps, an emergency medical helicopter is often indicated from NACA 3. The NACA score is divided into the following categories (▣ Table 37.1).

▣ **Table 37.1** NACA score of the National Advisory Committee for Aeronautics for the assessment of injury severity[a]

NACA category	Patient condition	Examples of injuries
0	No injury or illness	This category is often omitted without replacement or replaced by NACA I,
I	Minor condition No medical intervention required	e.g. minor skin abrasion
II	Mild to moderately severe condition Outpatient medical assessment, but usually no emergency medical intervention required	E.g. fracture of a finger, moderate lacerations; dehydration
III	Moderate to severe, but not life-threatening condition Inpatient treatment required, often with emergency medical measures on site	E.g. femoral fracture; mild stroke; smoke inhalation
IV	Severe condition, where the development of a life-threatening condition in the short term cannot be excluded In most cases, emergency medical care is required	E.g. spinal injury with neurological deficits; severe asthma attack; drug poisoning
V	Acute life-threatening condition	E.g. grade three traumatic brain injury; severe myocardial infarction
VI	Cardiopulmonary resuscitation	
VII	Death	

[a] Modified after Wikipedia “NACA-Schema” (2013)

Conclusion

Emergencies in mountainous terrain pose particular challenges for rescue personnel and especially for emergency physicians. Physical hazards and organisational constraints often limit the scope of emergency medical interventions. Both ground-based and air rescue physicians must be aware of these limitations and adapt their management accordingly. They must be able to assess each situation in its entirety.

As a member of a mountain rescue team, the physician is required not only to act as an emergency physician but is also responsible for his or her own safety and that of the team. This must not be compromised by carrying out non-vital medical interventions. Mountaineering and rescue technical competence, knowledge of specific accident scenarios in the mountains, as well as compliance with legal and organisational requirements (air rescue operators and mountain rescue organisations) and many years of experience, are essential prerequisites for successful work as a mountain rescue physician.

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Possibilities and Limitations of Terrestrial Emergency Medicine in Alpine Terrain

Bernhard Ziegler and Alexander Egger

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Since the beginnings of emergency medicine, the basic principle has been 'the doctor should reach the emergency patient as quickly as possible'. Although prolonged on-site care has recently been increasingly questioned and rapid evacuation in the sense of 'scoop and run' is advocated in many situations, in emergencies in alpine terrain, long and complex transportation often leaves no alternative but to stabilise and treat the patient at the scene. For this reason, the following section will discuss emergency care in alpine environments.

The fundamental skills required for medical emergency interventions are even more important in alpine than in urban settings. Emergency patients are too ill or injured, and the conditions too challenging, to attempt medications or techniques where extensive experience is lacking. Therefore, emergency procedures must be learned under the supervision of experienced practitioners in a hospital setting.

Unfortunately, there are only a few scientific publications on alpine emergency medicine, most of which are case reports (Dembeck et al. 2012; Boue et al. 2014). A key reason for this limited data is the low incidence of alpine emergencies requiring terrestrial physician-led interventions. The vast majority of alpine emergency patients (>90%) in German-speaking countries are cared for by the organised helicopter rescue service. This topic is addressed in a separate chapter in this book (▶ Chap. 39).

Limited diagnostic and therapeutic options under adverse environmental conditions, as well as long transport times, make care in alpine terrain similar to care in military operations, for which more evidence-based data are available. In this context, the sense of responsibility and improvisational skills of the rescue team are crucial prerequisites for the successful treatment of an alpine emergency patient.

38.1 Operational Planning and Preparation

Emergency patients in alpine terrain who require physician-led care are often located in areas that are difficult to access. In addition, weather conditions in alpine environments can be extremely adverse or deteriorate rapidly. Thorough preparation for emergencies is therefore essential. In addition to the usual information—*where*, *who*, *when*, *what* and *how many* are affected by the emergency—it is vital to obtain information in advance regarding accessibility of the incident site, options for evacuation, and the anticipated duration of the operation.

A physician-led operation in alpine terrain requires adequate preparation, despite the need for rapid deployment. The emergency physician does not necessarily have to be part of the first response team.

38.2 Diagnostics and Initial Measures

In principle, diagnostic and therapeutic interventions in alpine environments should adhere to internationally recognised evidence-based emergency standards, such as Prehospital Trauma Life Support (PHTLS) and the European Trauma Course (ETC) for trauma patients, and Advanced Life Support (ALS) of the European Resuscitation Council for peri-arrest situations.

Given the specific circumstances already mentioned in alpine settings, these guidelines often require adaptation. ICAR MEDCOM seeks to address these unique alpine conditions in its recommendations for the medical management of emergency patients (Elsensohn et al. 2006; Paal et al. 2007;

Ellerton et al. 2014; Tomazin et al. 2011; Schön et al. 2020; Musi et al. 2021; Sumann et al. 2020; Pasquier et al. 2023).

Due to the likely delayed arrival of the rescue team at the scene, the emergency is often already advanced and easier to assess, but at the same time, patients with similar injury patterns who would have been stabilised in the resuscitation room in urban settings with short transport times may be in a life-threatening condition. The initial steps upon arrival at the scene are to assess the situation with regard to personal safety (e.g. risk of secondary avalanches, falls, rockfall, etc.) and to evaluate the mechanism of injury.

> Upon arrival at the scene, attention should be paid to personal safety and the presumed mechanism of the accident.

38.2.1 First Impression (5-Second Round)

Initially, a rapid assessment of vital functions as 'stable' or 'critical' can be made by addressing, observing and touching the patient. In accordance with ALS guidelines, if a patient shows no signs of life but survival is still considered possible, cardiopulmonary resuscitation should be initiated immediately (Paal et al. 2012).

For all other patients, a systematic assessment should be performed according to the ABCDE approach (American College of Surgeons 2013). However, if there is obvious massive external bleeding, immediate control of the haemorrhage by compression or tourniquet application takes priority. Known in English as 'critical bleeding', this life-threatening haemorrhage should be controlled by direct manual pressure or a pressure bandage as a first measure.

38.2.2 A for Airway

During the initial assessment, it is sufficient to determine whether the airway is clear, at risk or obstructed. If the airway is obstructed or at risk, it must be cleared or maintained immediately. Airway assessment in trauma patients should always be accompanied by cervical spine stabilisation. The airway is opened by tilting the head back (unless a cervical spine injury is suspected) and lifting the chin. In unconscious patients, the so-called Esmarch manoeuvre can be used to temporarily maintain airway patency.

38.2.3 B for Breathing

After opening and clearing the airway by tilting the head back (provided there is no suspicion of cervical spine injury) and lifting the chin, the effectiveness of breathing is assessed using three senses: visual (chest or abdominal movement), auditory (breath sounds) and tactile (airflow and chest rise and fall). The initial assessment of breathing should focus on penetrating vs. blunt injuries, skin colour, chest movement (bilateral?), respiratory rate and effort and breath sounds (e.g. vesicular vs. bronchial breathing). This allows classification as adequate or inadequate breathing. A pulse oximeter may be used as a technical aid, bearing in mind its limitations in this setting. If abnormal breathing (e.g. agonal respiration) or absence of breathing is detected, resuscitation measures must be initiated immediately.

38.2.4 C for Circulation

Assessment of circulatory status requires even greater attention and expertise under adverse conditions. Conventional criteria such as skin colour and capillary refill time are only of limited value in cold environments. However, blood pressure, pulse quality and centrally assessed capillary refill time (e.g. at the sternum) can still provide an indication of circulatory status under these circumstances. Depending on the mechanism of injury and injury pattern, circulatory instability must be anticipated. In addition to obvious external bleeding, occult blood loss due to internal injury must also be considered. Potential blood loss from injured organs or fractures of large bones should not be underestimated.

> The initial assessment and management are based on the ABCDE approach, in accordance with internationally recognised guidelines for the care of critically ill and injured patients.

38.2.4.1 Circulatory Stabilisation Measures

External bleeding is immediately controlled, if necessary, by direct digital pressure or subsequently by applying a pressure bandage. Another option is the application of gauze dressings impregnated with haemostatic agents (e.g. Quickclot® or HaemCon®). In the case of severe arterial bleeding with an identifiable vessel, haemostasis using a vascular clamp should also be considered. Recent studies have shown that intravenous administration of the antifibrinolytic agent tranexamic acid can be beneficial in the prehospital setting for the management of massive haemorrhage (Roberts et al. 2012). This therapeutic option is also suitable for use in alpine environments due to its small pack size and ease of administration.

Circulatory therapy by means of volume replacement is only possible to a very limited extent in alpine terrain for logistical reasons (e.g. weight, storage). At present, the evidence regarding the type of volume replacement fluid is inconclusive. In the case of a haemodynamically unstable patient with traumatic brain injury, the ICAR-MEDCOM recommendations suggest, for logistical reasons (small pack size), the use of a small amount of hypertonic solution (Sumann et al. 2020), although the S3 guideline on polytrauma from the German Trauma Society (DGU) recommends the exclusive use of crystalloid solutions (DGU 2022). Otherwise, the currently accepted recommendation of permissive arterial hypotension in polytrauma patients is likely to be followed.

Another option for circulatory stabilisation, for example in patients with traumatic brain injury, is the administration of catecholamines (Sumann et al. 2020). Due to the high risk of adverse effects, catecholamines should be administered continuously and in diluted form. Bolus administration should be avoided except in cases of cardiopulmonary resuscitation (1 mg epinephrine diluted in 10 ml) and anaphylactic shock (0.5 mg epinephrine intramuscularly). Continuous administration can, for example, be achieved in alpine settings by adding the catecholamine to an infusion (e.g. 250 ml Ringer's solution), which is then wrapped with a blood pressure cuff and continuously infused by applying pressure. Repeated blood pressure measurements should be performed to assess the effect of catecholamine therapy.

38.2.5 D for Disability

The next step is to assess the neurological status. This includes evaluation of central nervous system function, response to verbal and painful stimuli using the Glasgow Coma Scale, pupillary function, and peripheral neurological status with respect to motor function and sensation. After recording these vital parameters, the patient can be categorised as *stable, at risk* or *unstable*.

38.2.6 E for Exposure

The patient is examined from head to toe, both anteriorly and posteriorly, in relation to the emergency event. If a complex or unclear injury pattern is suspected, a full-body examination is essential. However, care must be taken to avoid excessive time loss and further cooling of the patient, for example by undressing. Accidental hypothermia is a significant problem in any outdoor emergency and, in trauma patients, increases the tendency to bleed (approximately 10% more bleeding with a drop in core body temperature from 37 to 36 °C) and mortality (Rajagopalan et al. 2008). After this initial assessment and management ('primary survey', ABCDE), an impression of the injury pattern and severity should have been obtained. This forms the basis for further therapeutic measures and planning for evacuation. ▫ Table 38.1 provides an overview of the ABCDE algorithm.

▫ **Table 38.1** ABCDE algorithm

A	Airway with C-Spine Protection	Securing the airway and cervical spine
B	Breathing	Stabilising respiration
C	Circulation	Circulatory stabilisation and haemorrhage control
D	Disability	Assessment using the Glasgow coma scale (GCS) and evaluation of pupillary response
E	Exposure and environment	If necessary, undressing, body check, assessment of the environment, thermal management

38.3 Special Measures

38.3.1 Airway Management and Ventilation

As in the 'standard emergency setting', endotracheal intubation should only be performed by a trained rescuer. The often adverse alpine conditions, such as unfavourable patient positioning, poor lighting and temperatures that can affect equipment, present significant challenges even for experienced anaesthetists and ultimately result in a higher complication and mortality rate compared to urban environments.

For physicians with less advanced airway management experience, alternative methods, such as a laryngeal mask or tube, should be considered. However, even for experienced practitioners, an appropriate alternative airway device should be available. In principle, the indication for airway management and subsequent ventilation should be made cautiously, particularly in view of the likely difficulty for continuous ventilation during evacuation.

If there are already indications of a pneumothorax prior to the initiation of positive pressure ventilation (e.g. diminished breath sounds, flail chest, subcutaneous emphysema), the development of a tension pneumothorax requiring intervention should be anticipated. In such cases, the placement of a chest drain is necessary. In alpine terrain and with minimal equipment, a minithoracotomy at the usual site (e.g. fifth intercostal space, mid-axillary line) is recommended.

Subsequently, the (haemato-) pneumothorax can be drained using an endotracheal tube with an internal diameter of 7.0 mm. Care must be taken to ensure correct fixation and to avoid occlusion of the drain during transport. For ventilation during evacuation, pneumatically operated ventilators are available. Otherwise, manual ventilation using a bag-valve mask with a PEEP valve must be performed.

Induction of anaesthesia and ventilation should be done only when absolutely necessary when evacuating in difficult terrain.

38.3.2 Anaesthesia and Procedural Sedation and Analgesia

Anaesthesia is required for endotracheal intubation in both awake and obtunded patients with preserved protective reflexes. However, anaesthesia should only be carried out by physicians with relevant experience, and the indication should be made cautiously due to the challenging conditions in mountain environments (Braun et al. 2010).

Due to frequently low temperatures, problems may arise when administering medications. Tracheal intubation equipment may be cold or frozen, and the function of battery-powered laryngoscopes may be impaired. The same range of anaesthetic agents as in conventional emergency medicine is suitable, e.g. midazolam/ketamine or fentanyl/propofol. Muscle relaxants are appropriate in the hands of experienced practitioners (Paal et al. 2010).

Procedural sedation and analgesia, especially for painful procedures such as repositioning or immobilisation, are not only important for shock management but are also an ethical imperative. S-ketamine at a dose of 0.25–0.5 (−1) mg/kg body weight is undoubtedly the agent of choice (Sumann et al. 2020), as it provides efficient, rapid, and safe analgesia. In many cases, repositioning and subsequent well-executed splinting of the extremity are sufficient to achieve adequate pain relief for the remainder of the evacuation. If this is not the case, titrated administration or short infusion of 5–7.5–15 mg piritramide is suitable for ongoing pain management during transport.

Ketamine should be combined with a benzodiazepine, e.g. midazolam 0.03–0.05 mg/kg body weight administered beforehand, to reduce the hallucinogenic effects of ketamine (Ellerton et al. 2009a). The dosage of the medications administered requires experience and should be titrated. It is important to note that, especially in haemodynamically unstable and hypothermic patients, circulation time is prolonged, and therefore a longer interval than in normothermic, haemodynamically stable patients should be observed before repeat dosing to avoid overdose. Other analgesics, such as fentanyl and morphine, as well as non-steroidal analgesics, may also be used (Ellerton et al. 2013). Oral opioids used in oncology (e.g. fentanyl) in the form of lozenges (e.g. Actiq®) or sublingual tablets (e.g. Effentora®) are also suitable for use in alert patients as strong analgesics.

To avoid the use of cold medications, it is advisable not to carry them in the emergency backpack, where they are exposed to the cold, but rather to transport them close to the body.

It should be borne in mind that patients who are under sedation or anaesthesia cool down more rapidly. Several factors contribute to this. Firstly, central thermoregulation is altered, so that, for example, sedated patients only perceive colder temperatures as cold. Secondly, shivering is reduced under procedural sedation and analgesia and is completely absent under anaesthesia; in addition, blood vessels are dilated. Finally, patients under anaesthesia are ventilated with cold ambient air. These effects of procedural sedation and analgesia are dose-dependent, i.e., mild procedural sedation and analgesia have the least negative impact on thermoregulation, while anaesthesia maximally inhibits both central and peripheral thermoregulation (e.g., shivering and vasoconstriction). It appears that, due to its pharmacological profile, ketamine impairs thermoregulation the least (Brugger et al. 2013).

> When performing anaesthesia or procedural sedation and analgesia, close monitoring of vital parameters (consciousness, respiration, and circulation) by means of clinical examination and monitoring is essential.

Monitoring can only be carried out to a limited extent in mountain environments. For example, continuous monitoring of oxygen saturation using pulse oximetry often does not function correctly for various reasons (e.g., movement, centralised circulation, UV radiation). ECG monitoring or non-invasive blood pressure monitoring may also not always be possible.

A defibrillator should be taken on alpine rescue missions, especially in cases of medical emergencies (Elsensohn et al. 2006). Small, lightweight semi-automatic defibrillators (AEDs), possibly with ECG monitoring for rhythm analysis, have proven highly effective.

38.3.3 Thermal Management

Accidental hypothermia significantly affects morbidity and mortality in emergency patients, and the risk of clinically relevant hypothermia is also considerable in mountain environments. Therefore, measures to prevent or reduce accidental hypothermia deserve special mention. For all alpine emergency missions, equipment for protection against cold, moisture and wind, and for longer operations (duration >1 h) possibly also for warming, should be carried.

A classic method of protection against cold, rain and wind in the mountains is the combined use of vacuum mattresses, aluminium rescue blankets, chemical heat packs, wool blankets, woollen hats and rescue bags. However, this classic protection is sometimes not possible, and the rescue team must improvise.

There are various other systems, such as a modified rescue foil and a chemically activated thermal blanket. The modified rescue foil has a special chamber design and is probably more efficient at retaining body heat than conventional aluminium rescue blankets. The chemically activated thermal blanket heats up within 10 min after opening the vacuum packaging and can provide warmth to the patient for several hours.

> The risk of hypothermia must be addressed with appropriate warming measures and by administering only prewarmed medications.

38.3.4 Positioning

Immobilisation and positioning of a traumatised patient can, in principle, be carried out as effectively in alpine environments as in urban settings. Accordingly, this measure also represents a key priority in the initial pain management of trauma patients. Furthermore, appropriate positioning and immobilisation can reduce blood loss, secondary neurovascular injury and the risk of soft tissue damage (Ellerton et al. 2009b).

For immobilisation and positioning, as well as for transport, the use of vacuum mattresses has proven most effective. In cases of suspected unstable pelvic injury, the application of a pelvic compression device is recommended to reduce blood loss (Heetveld et al. 2004; Sumann et al. 2020). Their small packing volume makes these devices particularly suitable for alpine emergency medicine.

There are differing recommendations regarding the indication for cervical spine (C-spine) collars. The S3 guidelines for the management of polytrauma patients do not mandate the application of a C-spine collar in the absence of the following symptoms: impaired consciousness, neurological deficit, cervical spine pain, or muscular rigidity in the cervical region (Bouillon et al. 2013). Other authors recommend C-spine immobilisation in the presence of certain mechanisms of injury, such as a fall from a great height. However, particular attention must always be paid to the potential for respiratory compromise or the risk of aspiration in patients with impaired consciousness and C-spine immobilisation.

38.3.5 Cardiopulmonary Resuscitation

In mountain emergency operations, it is not uncommon for the patient to be unresponsive. The decision to initiate cardiopulmonary resuscitation is, even in standard emergency settings, by no means always clear-cut or easy, and this is even more true in mountainous terrain. Additional factors, such as self-protection, the safety of the mountain rescue team, and prognostic considerations, such as hypothermia, play a significant role. The ICAR MEDCOM has issued recommendations for the initiation and termination of cardiopulmonary resuscitation in alpine environments (Paal et al. 2012; see also ◘ Table 38.2).

Due to the specific circumstances in mountainous terrain, such as a limited number of rescue personnel, restricted equipment, adverse environmental conditions and difficult, prolonged evacuation, the outcome of resuscitation efforts is less favourable compared to urban settings. A defibrillator can save the life of a patient in cardiac arrest if it is accessible within a few minutes (e.g. at ski lifts, mountain huts, or if first responders carry an AED).

◘ **Table 38.2** Termination of resuscitation after unwitnessed collapse. All three criteria must be met

1	No return of spontaneous circulation within 20 min of cardiopulmonary resuscitation
2	No shockable rhythm
3	No hypothermia or other special conditions justifying prolonged resuscitation

Cardiac arrest due to trauma in the alpine environment is, for the reasons mentioned above, associated with an extremely poor prognosis, unless the circumstances of the accident suggest one of the following accompanying factors: accidental hypothermia or lightning strike. In these two exceptional cases of cardiac arrest, the survival rate is higher and prolonged cardiopulmonary resuscitation is justified. In such cases, the use of mechanical chest compression devices can significantly improve the quality of cardiopulmonary resuscitation.

Although the decision to terminate or continue resuscitation must be made on a case-by-case basis, termination should be carried out by the responsible medical director of the rescue service or in accordance with locally applicable protocols.

38.4 Evacuation

The timing of the evacuation of an emergency patient from alpine terrain is an individual decision and depends on many factors. Stabilisation of vital parameters—although naturally desirable—cannot always be achieved. This means that, in such situations, evacuation must sometimes proceed even with unstable patients. Waiting for improved weather conditions, and thus the possibility of helicopter rescue, may in some cases be a viable alternative to ground evacuation (Pasquier et al. 2012).

Continuous monitoring and care by a physician, as well as appropriate monitoring, are mandatory in all cases, especially after the administration of potentially respiratory- or circulatory-depressant medications. During prolonged evacuation using specialised stretchers, particular attention must be paid to positioning the patient to avoid pressure sores and, if necessary, to the use of absorbent pads to prevent the patient from lying in a constantly moist environment in the event of incontinence.

Conclusion

Emergencies in alpine terrain require not only emergency medical knowledge and mountaineering skills, but also a high degree of improvisational ability and responsibility. Measures in accordance with international emergency care guidelines cannot always be implemented due to the circumstances. Nevertheless, basic interventions such as airway management, haemorrhage control, analgesia, and thermal management can provide effective assistance to the casualty in mountain environments.

However, as air rescue continues to expand in the field of mountain rescue, the number of exclusively ground-based mountain rescue operations will continue to decline, and experience in this area will decrease accordingly. Regular participation of mountain medicine specialists in mountain rescue exercises is therefore essential.

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39

Opportunities and Limitations of Alpine Helicopter Rescue

Guenther Sumann, Alexander Egger, and Bruno Durrer

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39.1 Advantages of Helicopter Rescue in Mountain Rescue

Helicopter Emergency Medical Services (HEMS) offer several key advantages over terrestrial mountain rescue. The time required for a mountain rescue operation is significantly reduced. Short response times enable early emergency medical treatment (Tomazin et al. 2012). Advanced emergency medical treatment can be initiated on site, and rapid transport to the most suitable destination hospitals is possible even over long distances. For multi-traumatised patients, the fastest possible admission to a trauma centre can be crucial for survival, whereas prolonged ground rescue operations under adverse weather conditions, even in cases of initially non-life-threatening injury, are associated with a high risk of mortality (Holzmeister 2017). In many helicopter rescue missions in the European Alps, severely injured patients can be transported to an appropriate destination hospital within the 'golden hour' (Marsigny et al. 1999; Scrimgeour 2003). This time frame is usually exceeded in purely terrestrial rescues. An analysis of the German Trauma Registry over a 10-year period demonstrated a positive independent survival benefit for patients following helicopter rescue missions (Andruszkow et al. 2014). Other studies have also shown a survival benefit when emergency medical helicopters are used in cases of severe trauma (Desmettre 2012; Zhu et al. 2018) and describe a clear benefit in mountain rescue operations (Ausserer et al. 2017).

A rescue line or winch operation by helicopter can be carried out quickly, even in very difficult terrain, and is also significantly gentler and safer for both patient and rescuer than a terrestrial abseiling operation, which can take hours. In large-scale, complex mountain rescue operations or avalanche missions, helicopters offer the possibility of transporting large numbers of rescue personnel and equipment safely to the scene within a short time (Tomazin and Kovacs 2003). In some cases, it may even be too dangerous for ground rescue personnel to reach the scene of the accident. If the exact location of the emergency is not accurately known, a search flight can make it easier to locate the accident victim. All these advantages of helicopter rescue, of course, require suitable weather and visibility conditions for flying.

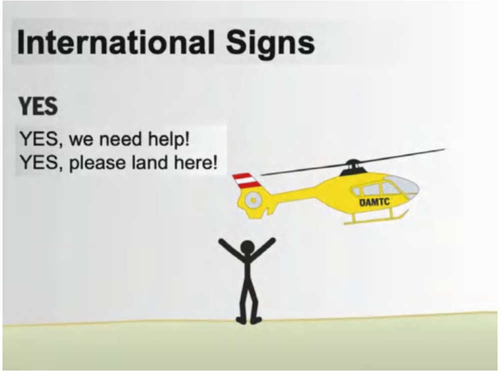
Recently, drones have been used in mountain rescue. This enables casualties to be located from the air even when helicopters are unable to fly, allowing rescue operations to be better planned (Karaca et al. 2017).

39.2 Alerting and Briefing

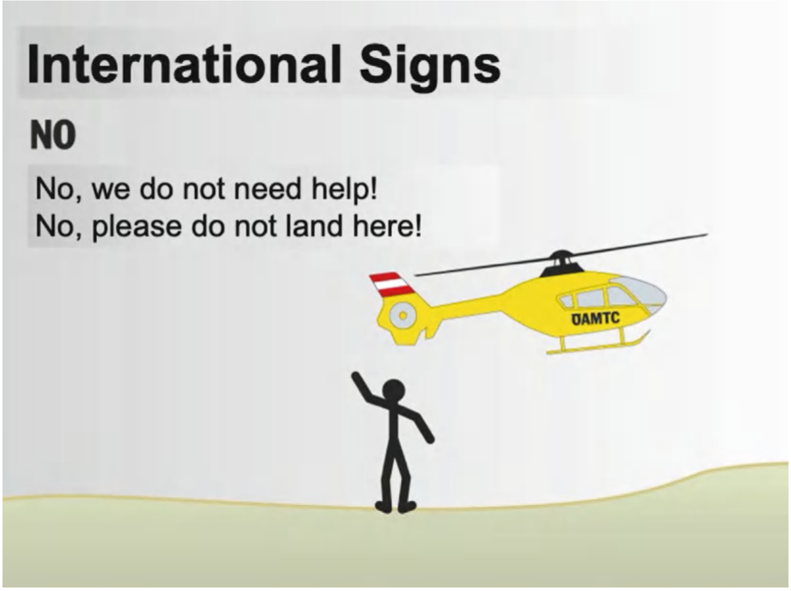
The alerting of helicopter rescue services is usually coordinated via public emergency dispatch centres or the dispatch centres of air rescue operators. When alerting for a mountain helicopter mission, it is important to provide as much additional information as possible regarding terrain characteristics, obstacles, ropes, visibility and weather conditions. Ropes must always be mentioned, even if it is assumed that the pilot is already aware of them. In marginal flying conditions, it is up to the pilot to decide, at the latest when on site, whether the mission can be carried out. The location of the emergency should be specified as precisely as possible, and GPS coordinates should always be provided if available.

During the approach phase, the caller should, if possible, remain reachable by phone and ensure mobile network coverage at their location. Often, the informant will be called from the cockpit when the helicopter is approaching the scene of the emergency so that further information can be exchanged. During the search phase, the view from the air can be extensive, and the location may be in the shade. Therefore, the person providing guidance should make themselves visually noticeable when the helicopter comes into view. Brightly coloured clothing that can be waved above the head or smoke bombs are best for this, provided the helicopter is still at a safe distance. Once the emergency site has been identified from the air, the helicopter will circle or hover above the informant ('high reconnaissance') while the crew assesses the situation. At this stage, the informant should clearly signal whether help is needed (YES, international signal; ◘ Fig. 39.1). Mountaineers who are unexpectedly circled by a rescue helicopter and do not require assistance should make it absolutely clear that they do not need help (NO, international signal; ◘ Fig. 39.2). Helicopter crews are often confused during searches by people waving, who may inadvertently give the impression that they require assistance.

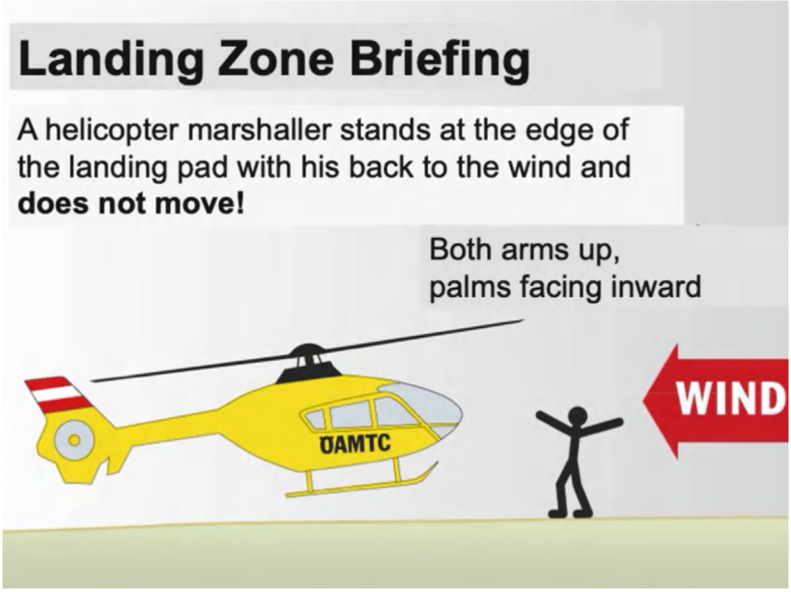
During landing in winter, the helicopter pilot must have a marshaller who remains motionless in front of the helicopter and preferably kneels down. The marshaller should position themselves so that the wind is blowing at their back, allowing the helicopter to land into the wind (◘ Fig. 39.3). Blowing up powder snow can cause the pilot to lose visual reference to the ground, making a landing without a marshaller impossible (i.e. "white out") (◘ Fig. 39.4).



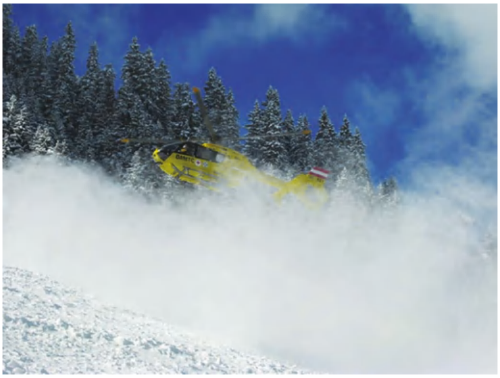
◘ **Fig. 39.1** YES, international signal. (Reproduced with the kind permission of Christophorus Air Rescue Association [CFV])


International Signs
NO
No, we do not need help!
No, please do not land here!
ÖAMTC

◘ **Fig. 39.2** NO, international signal. (Reproduced with the kind permission of Christophorus Air Rescue Association [CFV])


Landing Zone Briefing
A helicopter marshaller stands at the edge of the landing pad with his back to the wind and does not move!
Both arms up, palms facing inward
ÖAMTC
WIND

◘ **Fig. 39.3** Helicopter marshalling. (Reproduced with the kind permission of Christophorus Air Rescue Association [CFV])



◘ **Fig. 39.4** ‘White out’

After landing, neither the marshaller nor any other person may approach the running rotor without being instructed to do so by a crew member. Under no circumstances should hands or long objects (e.g. skis, poles) be raised (◘ Fig. 39.5). Depending on the helicopter type and the slope, the main rotor may dip close to the ground, so the helicopter should only be approached from lower ground (◘ Fig. 39.6).

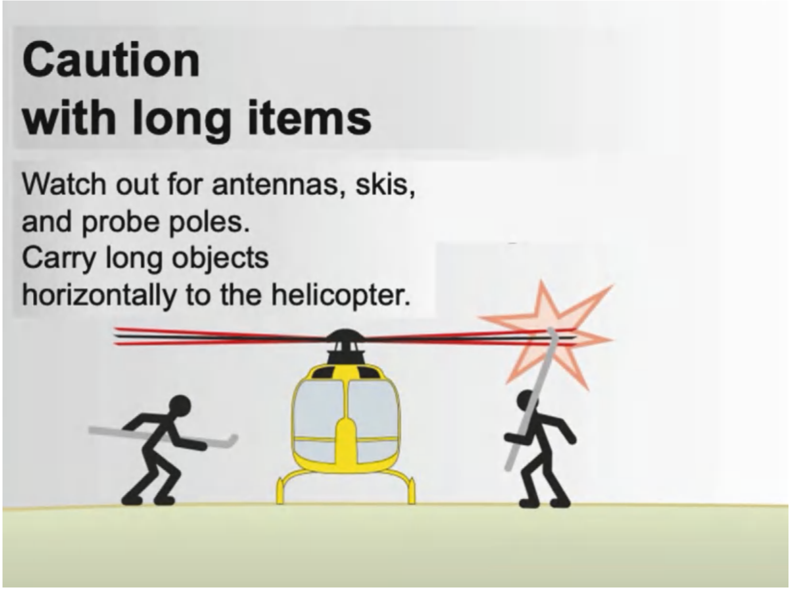

Caution
with long items
Watch out for antennas, skis,
and probe poles.
Carry long objects
horizontally to the helicopter.

Fig. 39.5 Caution with long objects. (Reproduced with the kind permission of Christophorus Air Rescue Association [CFV])

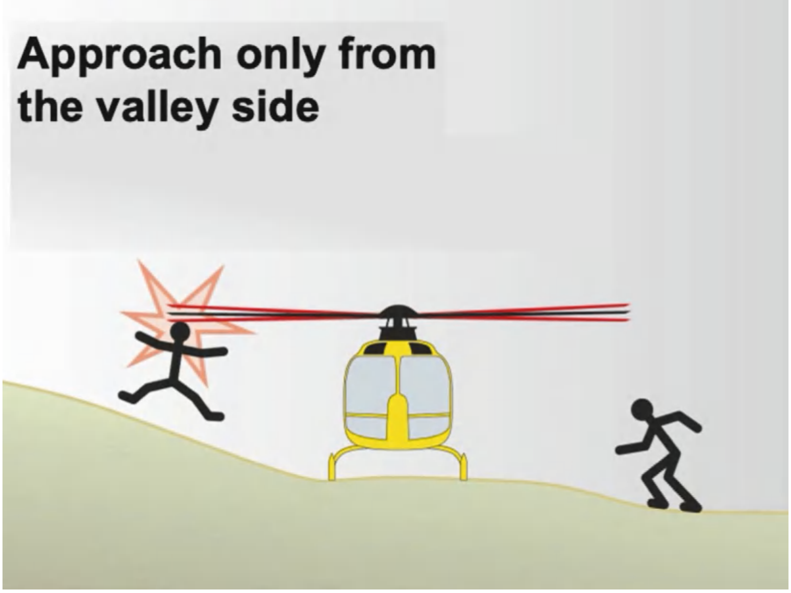

Approach only from
the valley side

Fig. 39.6 Approach only from the valley side. (Reproduced with the kind permission of Christophorus Air Rescue Association [CFV])

39.3 Helicopter Rescue Procedures in Mountainous Terrain

In recent years, helicopters have become increasingly specialised for challenging high-altitude rescues. While in Europe, twin-engine helicopters are required by law for use in populated areas and for approaching hospitals; missions at high altitudes (3700 m and above), in high temperatures and strong winds, often require particularly powerful helicopters to ensure safe rescue operations. After basic initial care and evacuation of the patient from the incident site by this more powerful rescue helicopter, the patient is handed over to the air ambulance helicopter for definitive emergency medical care and transport to the hospital. More recently, helicopter rescues have also been carried out in the Himalayas at extreme altitudes of over 7000 m (Pakistan 2008, Nepal 2010 and 2013) (Veillette 2016; Wilkinson 2015). Time will tell what the technical limits and possibilities of air rescue at extreme altitudes are.

In helicopter mountain rescue, the helicopter crew usually consists of three people: pilot, paramedic (HEMS crewmember) and emergency physician. For technically demanding mountain rescue operations and for helicopters equipped with a winch, the standard helicopter rescue crew may be supplemented by rescue specialists (e.g. mountain rescue guides) or winch technicians. For night operations, special night vision devices, searchlights and thermal imaging cameras are available. In Switzerland, approximately 90% of all mountain rescues are performed exclusively by helicopters (Durrer 1993a, b, 1994).

Once the emergency site in the mountains has been located, the helicopter hovers or circles above the scene ('high reconnaissance'), allowing the crew to assess the situation from the air and discuss the next steps. Depending on the terrain at the emergency site, various procedures are used in mountain air rescue:

39.3.1 Landing at the Emergency Site

If a landing at the emergency site is possible, the procedure for providing pre-hospital emergency care differs little from a ground rescue operation in the valley. All equipment carried in the helicopter is immediately available. The patient can receive optimal initial care from the entire air rescue team and be loaded directly into the helicopter.

39.3.2 Hover Loading of the Patient

On terrain with a slope of up to approximately 35° or on ledges, rescuers can leave the hovering helicopter and quickly reach the patient. After initial care, the patient is usually placed in a rescue bag or rescue triangle and, together with the rescue team, is airlifted out using the fixed rescue line. In some cases, the patient can also be loaded onto the rescue stretcher while hovering, or they can climb into the helicopter themselves with assistance. These manoeuvres are potentially hazardous and should only be performed in exceptional circumstances. They require a well-coordinated team and cannot be carried out with every type of helicopter. During the hovering procedure, the main rotor comes dangerously close to the uphill side. Any uncontrolled movements must be avoided, and untrained helpers must not enter the rotor circle. On ski slopes, the hovering procedure is not recommended, as even with the best possible barriers in place, the behaviour of the numerous skiers and onlookers cannot be reliably predicted. Hover loading is faster than a winch or line operation and is primarily used when time is critical.

39.3.3 Winch Rescue (25, 50 or 90 m)

If landing or hovering rescue is not possible, the emergency physician is lowered to the scene by the winch operator, either before or after the rescue specialist, using a climbing harness. Depending on the helicopter type, winch cables of 25, 50 or up to 90 m in length are available. The patient is rescued according to the nature of the injury, in either a climbing harness, a rescue triangle or a horizontal rescue bag, together with the physician on the winch cable. Subsequently, the patient is loaded into the helicopter either in flight or, more commonly, at an intermediate landing site, depending on the helicopter type.

Most winches are designed for a maximum of two persons. Evacuating a larger group, therefore, requires more time. An advantage is that a rescuer or physician can be dropped off during the initial approach.

39.3.4 Winch Descent Device: Variable Rope

At accident sites in narrow gorges or steep forested areas, it can be easier for the pilot if the rescuer or physician can abseil directly to the emergency site using a special descent device (winch descent device) on a static rope. The helicopter can then hover in the same position, making evacuation simpler. With this method, only one person can be lowered at a time.

39.3.5 Fixed Rope Procedure: Line and Longline Rescue

For a rope rescue, an intermediate landing site must be found nearby after the initial approach to attach the rescue rope to the central load hooks on the underside of the helicopter. The air rescue specialist, and usually also the physician, attach themselves to the rope and are flown to the emergency site. As with all rope rescue operations by helicopter, the air rescue specialist wears a radio helmet and provides the pilot with detailed instructions via radio during the rope flight.

Depending on the selected rope length, the helicopter remains safely outside or above any potential rock or icefall zones. Rope rescues—line up to 50 m or longline from 50 m—allow evacuation in a climbing harness, rescue triangle or rescue bag together with the physician and an experienced rescue specialist.

Simultaneous transport of up to five persons is possible and, compared to winch operations, is very time-efficient. Under overhangs, rescuers can use a telescopic pole to reach climbers. Stranded hang gliders, paragliders and base jumpers can be rescued with a rope length of approximately 75–100 m (depending on helicopter type) without dangerous downwash. The line system is also successfully used for evacuations from cable cars, gondolas and chairlifts. Longline operations are potentially hazardous due to significant pendulum movements and require a well-practised team (◘ Fig. 39.7).

39.3.6 Combined Ground-Air Rescue

When visibility is poor at the emergency site, it is often possible to transport rescuers and necessary equipment by helicopter below the cloud base, close to the emergency site. From there, the team can walk to the site. On-site, the weather situation can be better assessed, and occasionally, the helicopter can then be directed to the rescue location. Otherwise, the patient is transported terrestrially below the fog line (◘ Fig. 39.8).

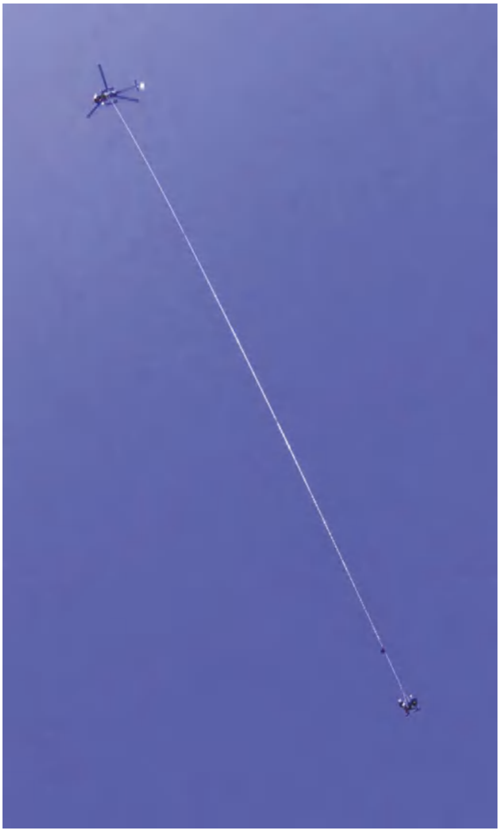


Fig. 39.7 Helicopter rescue using a longline

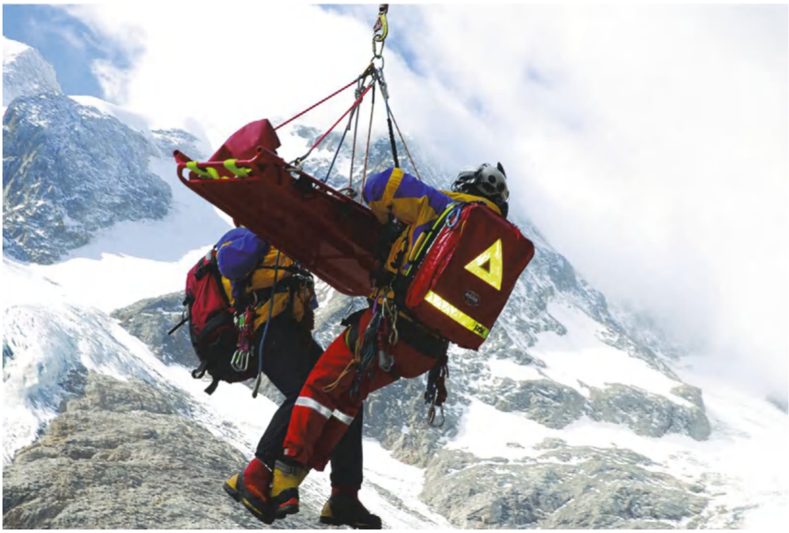


Fig. 39.8 Combined ground-air rescue by rope

39.4 Decision Algorithm for a Mountain Rescue Operation

39.4.1 Preparation of the Helicopter Rescue Physician

The operation begins with the alarm. In high mountain environments, especially in winter, the physician must wear thermal underwear, weatherproof clothing suitable for bivouacking and crampon-compatible boots with gaiters. Crampons, ice axe, shovel, headlamp and self-belay equipment are part of the personal gear. A map, an altimeter, a GPS and a spare battery for the smartphone can be very helpful, as can hot drinks. Enough equipment should be taken to survive an emergency bivouac. In avalanche operations, an avalanche probe, avalanche transceiver and avalanche airbag are part of the equipment.

Before a planned winch or rope operation, the climbing harness is put on prior to starting the mission. If there are multiple casualties, the medical equipment may need to be supplemented accordingly. If necessary, a second air ambulance or rescue helicopter with additional rescue specialists should be activated.

39.4.2 Decisions of the Helicopter Crew Above the Emergency Site

When approaching the accident site, the following options are available for the rescue operation.

39.4.2.1 Rescue Not Immediately Possible: Always a Team Decision

Occasionally, an operation cannot be carried out immediately due to objective hazards at the accident site or for aviation or technical rescue reasons. The safety of the rescue teams must always take absolute priority.

Objective Hazards at the Accident Site

Rescue is not immediately possible due to the risk of rockfall, icefall, or avalanches. Certain steep wall sections and couloirs, especially below ice cliffs, are highly prone to rock and icefall in the late afternoon. Therefore, rescue is only possible during the early, colder morning hours.

Aviation-Related Reasons

Visibility is poor or inadequate during night operations. The pilot’s training, experience, and knowledge of the terrain are limiting factors in challenging missions. Due to performance limitations at high altitude and in strong winds, it may be necessary to switch to a more powerful helicopter.

Technical Rescue

If there is a risk of falling at the emergency site, the team is supplemented by a rescue specialist, usually a mountain guide. Additional rescue specialists are required for longline, crevasse, avalanche, paragliding and parachute rescues. Some rescue operations must be carried out by ground rescue teams. In such cases, the helicopter provides only support and can transport personnel and equipment to the emergency site.

39.4.2.2 Rescue Immediately Possible

If landing at the emergency site is possible, the physician, together with the air rescue technician and pilot, can provide optimal care to the patient. If there is a risk of falling at the site, a rescue specialist is often deployed first to secure the emergency site. If possible, in a rope rescue operation, the physician and rescue specialist are dropped off together.

39.5 Medical Measures at the Emergency Site

The possibilities and limitations of providing initial medical care in high mountain environments depend greatly on terrain and weather, as well as on the skills of the medical rescue personnel. The scope of possible medical interventions is also influenced by the number of helpers at the emergency site. Whether a patient must be evacuated without medical care ('load and go') depends on the topography of the site, objective hazards, climatic influences, and the medical urgency. Even in difficult terrain, it is often possible to provide basic analgesia and immobilisation ('treat and run'). Ideally, full pre-hospital emergency care can be provided at the site ('stay and play') before technical evacuation (Durrer 1993a, b, 1994).

39.5.1 'Load and Go' in Difficult or Hazardous Terrain?

In the event of an objective hazard to the emergency site or imminent weather-related entrapment, immediate evacuation from the danger zone takes priority over initial medical care (Ellerton et al. 2009). In such cases, landing at the accident site may be possible. More often, however, the patient is evacuated either by line or winch, or is taken on board while the helicopter hovers. During landing or hovering pick-up, the helicopter temporarily enters the risk zone for possible rock or icefall.

Uninjured individuals wearing a climbing harness may, in exceptional cases, attach themselves to the winch or rope. Prior briefing via mobile phone or a lowered radio is absolutely essential. This approach has the advantage that no rescuers need to be dropped off. However, this procedure carries the risk of a fatal error by the mountaineer to be rescued and is not acceptable to all air rescue operators.

A free-hanging mountaineer is secured by rescuers on the line, then the helicopter takes up the load, and the mountain rope is cut with a knife (cutaway rescue).

Uninjured individuals without a climbing harness are secured by the rescuers in rescue harnesses or a rescue triangle and airlifted. During such a procedure, the rescuers often remain attached to the helicopter rope.

39.5.2 'Treat and Run' in Difficult Terrain?

Even in challenging terrain, rapid intravenous or intranasal analgesia (e.g. using a Mucosal Atomization Device, MAD®) and immobilisation (cervical collar, SAM® splint) can be administered. Providing adequate analgesia prior to evacuation is a humanitarian duty. Severely injured patients are most gently evacuated in a horizontal rescue bag on a vacuum mattress. However, this requires the rescuers to remain in the danger zone for a longer period and to detach themselves from the helicopter rope. In situations with a risk of falling, additional rescue specialists are required at the scene for safety tasks. The risk to the rescuers must always be weighed against the medical risk to the patient (■ Fig. 39.9).

39.5.3 'Stay and Play' in Difficult Terrain?

In principle, it is also possible in exposed terrain to provide initial emergency medical care to a patient at the scene before technical evacuation. However, many theoretical principles of emergency medicine from urban settings (e.g. Advanced Life Support [ALS], European Trauma Course [ETC]) can only be applied to a limited extent in the field. Even if there is sufficient space and personnel at the scene, it must be critically assessed whether it is truly advantageous to perform

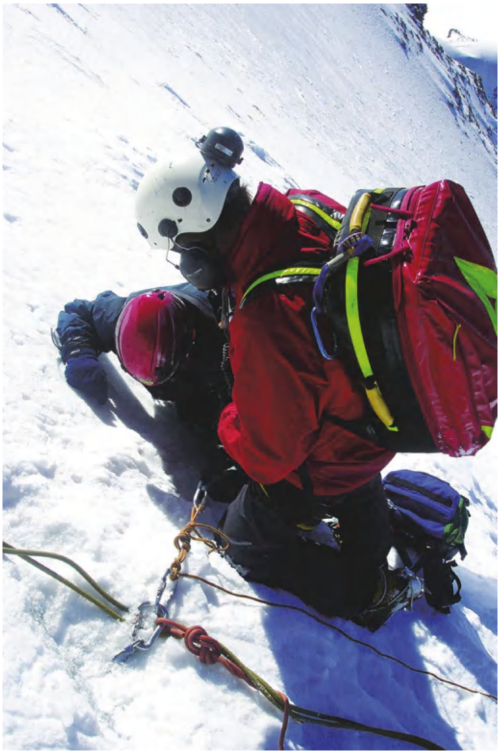


Fig. 39.9 'Treat and run' on a north face

complex and invasive emergency interventions in steep terrain prior to the rescue operation. Should unexpected difficulties or complications arise, subsequent rope evacuation may become significantly more challenging. When in doubt, rope evacuation should be carried out first, followed by definitive emergency medical care on flat terrain next to the landed helicopter.

39.5.4 Emergency Medical Interventions in the Field

39.5.4.1 Airway Management

Patients with serious and life-threatening injuries are only intubated in difficult terrain in exceptional cases prior to winch or long-line rescue. Sufficient personnel and double-secured tube fixation are required. When transporting an intubated patient in a rescue bag, the oxygen cylinder and transport ventilator with breathing circuits should be stowed and secured inside the horizontal bag. If the patient is breathing adequately, it is generally preferable to perform the technical rescue first, administering high-flow oxygen via mask, and then secure the airway afterwards. The airway can be kept open for technical rescue using an oropharyngeal, nasopharyngeal or supraglottic airway if necessary, and the patient can be airlifted in the rescue bag in the lateral position. On snow or in bright sunlight, it is helpful to shade the heads of both the doctor and the patient with a blanket to allow the eyes to adapt sufficiently before intubation. In the event of a tension pneumothorax, initial needle decompression can be performed at the scene. However, the indication for chest drain placement should then be established in good time for further management (Leigh-Smith and Harris 2005). The potential risks of intubation and other invasive procedures must always be critically weighed against the possible benefits under adverse conditions. The indication for prehospital intubation is subject to ongoing debate, and in any case, induction of anaesthesia and intubation in mountainous terrain should be performed exclusively by highly experienced emergency physicians (Haltmeier et al. 2017; Ausserer et al. 2017).

39.5.4.2 Cardiopulmonary Resuscitation

Provided that local conditions allow and the safety of the rescuers is ensured, resuscitation measures must be initiated at the scene in difficult terrain in the event of cardiac arrest, if there is a chance of survival. However, if no circulation can be restored in a normothermic patient after 20 min, cardiopulmonary resuscitation (CPR) may be terminated in accordance with regional guidelines (Lugnet et al. 2023). In cases of cardiac arrest with profound hypothermia (e.g. <28 °C), CPR should be continued, but may be interrupted for 5–10 min for rescue operations, depending on body temperature (Gordon et al. 2015). In challenging mountainous terrain, the practical feasibility of CPR can be a significant limiting factor. During evacuation with ongoing CPR, the use of an automated chest compression system (e.g. CorpulsCPR®, LUCAS®) is recommended (Thomassen et al. 2017; Egger et al. 2021).

39.5.4.3 Venous Access/Analgesia/Infusion

Equipment for venous access, as well as nasally administered analgesics, should be carried and easily accessed by the physician, for example, in a rescue vest or a waist pouch. The venous access can be disconnected after the administration of analgesia. Infusion solutions should primarily be carried by the physician within their clothing to protect them from cooling. However, infusion solutions cool so rapidly in the infusion line at sub-zero temperatures that maintaining an acceptable infusion temperature in the cold is almost impossible. Even ampoules can freeze quickly in the hand and become unusable. Establishing venous access can be very difficult in cold conditions. The time required for this, as well as for any further emergency medical interventions, must always be weighed against the risk of further hypothermia.

39.5.4.4 Protection Against Hypothermia

Injured individuals cool down rapidly; therefore, even during helicopter rescue operations, which are usually carried out quickly, care must be taken to ensure adequate protection against further cooling. In addition to heat packs and hot drinks, insulating layers should be used. If the casualty's clothing is wet, wrapping them in a vapour-impermeable covering can achieve the same warming effect as changing into dry clothing (Henriksson et al. 2012). Changing clothing should only be performed in relatively calm and sunny conditions, as there is a risk of rapid further cooling. Plastic sheets with air bubbles (i.e. bubble wrap) have also proven effective in practice. The patient must be protected from the wind as efficiently as possible. Modern rescue bags are made of thermal insulation material and provide good protection. During rope rescues in winter, snow is often blown onto rescuers and patients. The resulting moisture on the face is exposed to high wind-chill factors during winch flights at corresponding wind speeds and low temperatures and is particularly susceptible to frostbite. At low temperatures and in windy conditions, rope rescue distances should therefore be kept as short as possible, and rescuers must always wear gloves.

39.5.4.5 Immobilisation

Where possible, all seriously injured patients, especially those with spinal injuries, should be transported on a vacuum mattress in a rescue bag. This allows for almost any position to be stabilised. Cervical collars can be applied in virtually any terrain. Extremities can be immobilised using rollable lightweight splints, such as SAM® splints.

39.5.4.6 Reductions

Dislocations of fingers, patella and shoulder can be reduced at the scene by experienced emergency physicians. Technical rescue is then easier. In particular, with shoulder dislocations, positioning and evacuation may sometimes be impossible without reduction.

39.5.4.7 Monitoring

Depending on the severity of injury, full monitoring (i.e. blood pressure, ECG, oxygen saturation, temperature measurement) at the scene is desirable. However, the benefit during technical rescue is often questionable. During winch flights by helicopter, there is unlikely to be the opportunity for medical intervention.

39.6 Rescue Risk

The medical urgency in difficult and hazardous rescues must always be carefully weighed against the subjective risks (e.g. skills and experience of the helicopter crew and rescuers) and objective rescue risks (e.g. nighttime, weather, avalanches, rock/ice fall) (◘ Fig. 39.10). Uninjured, well-equipped mountaineers can sometimes safely bivouac overnight and be flown out early the following morning when there is much less risk of rockfall. In the case of severely injured patients, however, the full scope of justifiable risk is appropriate. The final decision always rests with the rescue team. In poor weather, primary transport by cable car and ambulance to the nearest hospital is preferable to a hazardous flight with landing and potential entrapment in inaccessible terrain.

Under rescue stress, double caution (e.g. rotor blades, flight obstacles) and triple checking (e.g. knots, carabiner security, patient safety) are essential. False heroism among pilots, rescue specialists and physicians risks life. The instinct for self-preservation must always take precedence over the urge to rescue.

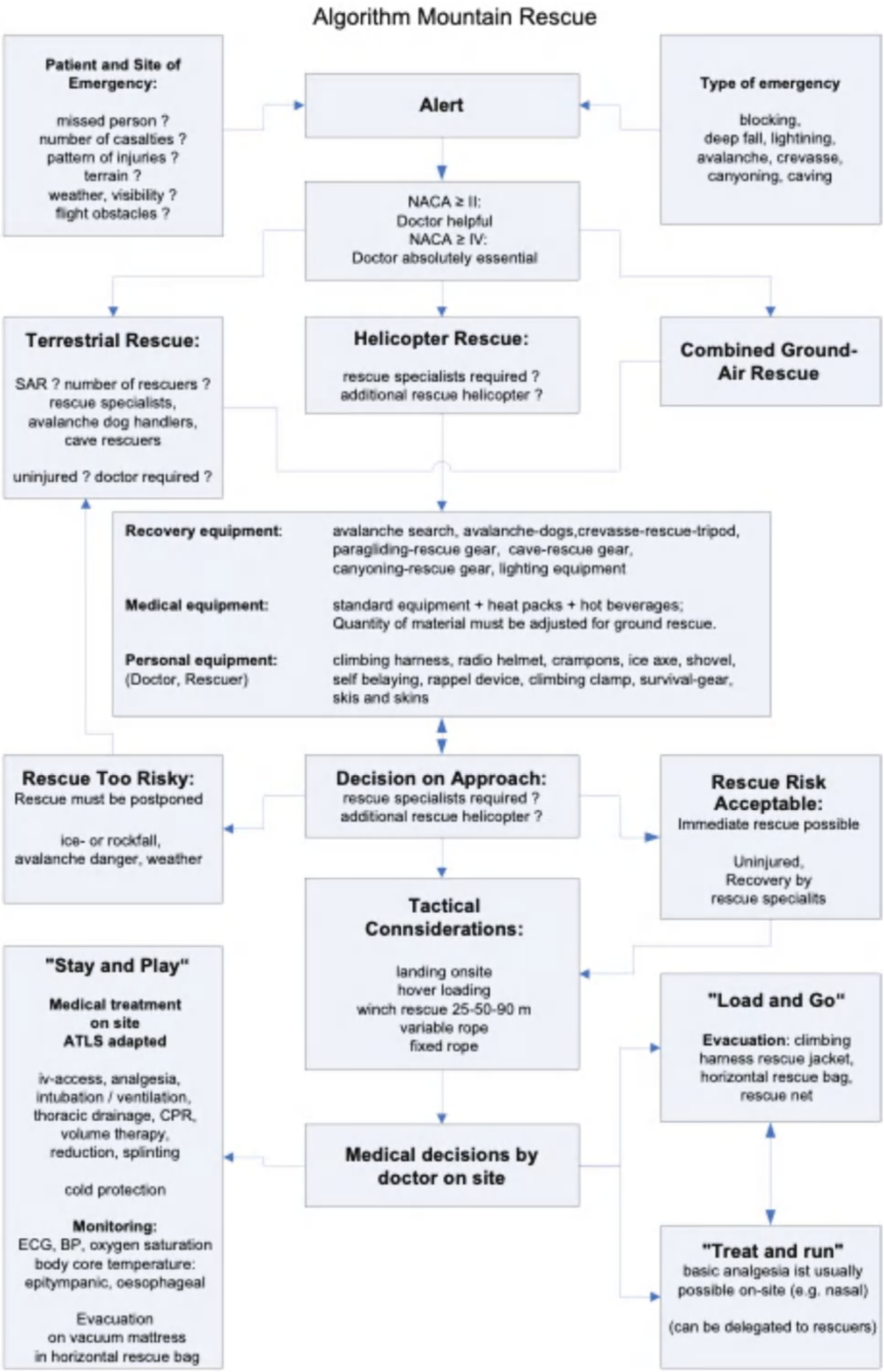

Algorithm Mountain Rescue
Patient and Site of Emergency:
missed person ?
number of casalties ?
pattern of injuries ?
terrain ?
weather, visibility ?
flight obstacles ?
Alert
Type of emergency
blocking,
deep fall, lightning,
avalanche, crevasse,
canyoning, caving
NACA ≥ II:
Doctor helpful
NACA ≥ IV:
Doctor absolutely essential
Terrestrial Rescue:
SAR ? number of rescuers ?
rescue specialists,
avalanche dog handlers,
cave rescuers
uninjured ? doctor required ?
Helicopter Rescue:
rescue specialists required ?
additional rescue helicopter ?
Combined Ground-Air Rescue
Recovery equipment:
avalanche search, avalanche-dogs,crevasse-rescue-tripod,
paragliding-rescue gear, cave-rescue gear,
canyoning-rescue gear, lighting equipment
Medical equipment:
standard equipment + heat packs + hot beverages;
Quantity of material must be adjusted for ground rescue.
Personal equipment:
(Doctor, Rescuer)
climbing harness, radio helmet, crampons, ice axe, shovel,
self belaying, rappel device, climbing clamp, survival-gear,
skis and skins
Rescue Too Risky:
Rescue must be postponed
ice- or rockfall,
avalanche danger, weather
Decision on Approach:
rescue specialists required ?
additional rescue helicopter ?
Rescue Risk Acceptable:
Immediate rescue possible
Uninjured,
Recovery by
rescue specialits
Tactical Connsiderations:
landing onsite
hover loading
winch rescue 25-50-90 m
variable rope
fixed rope
"Stay and Play"
Medical treatment
on site
ATLS adapted
iv-access, analgesia,
intubation / ventilation,
thoracic drainage, CPR,
volume therapy,
reduction, splinting
cold protection
Monitoring:
ECG, BP, oxygen saturation
body core temperature:
epitympanic, oesophageal
Evacuation
on vacuum mattress
in horizontal rescue bag
"Load and Go"
Evacuation: climbing
harness rescue jacket,
horizontal rescue bag,
rescue net
Medical decisions by doctor on site
"Treat and run"
basic analgesia ist usually
possible on-site (e.g. nasal)
(can be delegated to rescuers)

Fig. 39.10 Mountain rescue algorithm. *CPR* cardiopulmonary resuscitation; *ETC* European Trauma Course; *ATLS* Advanced Trauma Life Support; *NACA* National Advisory Committee for Aeronautics: here, NACA score for assessment of injury severity

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40

Emergency Equipment for Mountaineers and Mountaineering Physicians

Alexander Egger and Franz Berghold

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40.1 International Standards

The available evidence, a recommendation of the International Commission for Alpine Rescue (ICAR) entitled 'The Mountaineer's, Mountain Guide's and Mountaineering Doctor's Rucksack Pharmacy' from 1998, is now over 25 years old. It is referenced in the 'Consensus Guidelines on Mountain Emergency Medicine and Risk Reduction' of the two international alpine medicine umbrella organisations, ICAR MEDCOM (International Commission for Mountain Emergency Medicine) and UIAA MEDCOM (Medical Commission of the International Mountaineering and Climbing Federation). The modular system of three complementary packages recommended at the time takes into account the user's knowledge and level of training and remains relevant today. The contents, the equipment and medications, carried have however changed in line with new developments (Elsensohn et al. 2011; Reisten et al. 2017).

40.2 How Much Should be Taken?

The scope of emergency equipment varies according to the care strategy and the risk potential of the activity. In addition, the user's level of training and formal authorisation influence the equipment carried. The contents of a rucksack pharmacy for an expedition to remote regions of the world will be much more extensive and tailored to a wide range of emergency, general and high-altitude medical issues than the equipment required for a multi-day tour in the Central Alps. It cannot be assumed that every member of a guided group carries basic equipment. So, to ensure that in the event of multiple casualties (e.g. rockfall affecting the group), logistic planning to provide adequate care should be considered and actions taken to maximise appropriate material within the carrying capacity of the group (Wagner et al. 2022).

How many first aid kits should be available per climbing team or activity group? The answer to this question applies generally to all alpine activities. Every member should always carry a first aid kit in their rucksack, not only for practical grounds but also on philosophical and ethical grounds, unless the group's decision is otherwise.

40.3 What Should Be Taken?

A fundamental distinction should be made between the basic alpine emergency equipment that every mountaineer should always carry, including a basic medical kit (first aid kit), and specialised equipment intended for medically trained personnel (e.g. mountain rescuers, paramedics, nurses and doctors). The provision of equipment for conducting an expedition must be considered as a separate topic, as numerous additional factors influence the planning process in this situation.

Injuries and illnesses are significantly more serious in alpine environments than in easily accessible valley regions. The fact that, in alpine areas, the time window until the arrival of professional rescue services is considerably longer than in urban settings. This makes it virtually impossible to expect immediate first aid measures to be carried out by the mountain rescue service. As is recognised in avalanche rescue, it's the companions who will have the opportunity to do immediate first aid. So, in addition to personal protective equipment (adapted to the specific alpine activity), it is advisable to carry both a basic emergency kit and a first aid kit, including a rucksack pharmacy. The basic emergency kit enables the alerting of rescue services, precise determination of the current location, and protection against the elements.

Basic Alpine Emergency Kit

This includes
- Mobile phone (with power bank for charging, if necessary)
- GPS device (if this function is not covered by the mobile phone), map, compass
- Gloves and a hat for protection against the cold
- Whistle
- Light source (e.g. headlamp)
- Sun protection, sunglasses
- Bivouac sack for 2 people
- Drinks, carbohydrate foods (e.g. dried fruit, energy bars)

40.4 Suggested First Aid Kit for Mountaineers

Every basic alpine emergency kit should also include a first aid kit. This enables the mountaineer to manage minor wounds and injuries (e.g. removal of foreign bodies, blisters on the feet, and sprains), provide an appropriate level of thermal protection and safely carry out life-saving immediate measures.

The items that a first aid kit should contain are listed in the following overview.

First Aid Kit
- Resuscitation face shield
- Triangular bandage
- Aluminium emergency blanket
- Disposable gloves (4)
- Emergency bandage ('Israeli bandage') or alternatively gauze bandage + sterile wound dressing
- Plasters of various sizes
- Self-adhesive tape bandage (cohesive fixation bandage)
- Pair of scissors
- Pair of tweezers
- Additionally, the inclusion of gel blister plasters and a universal splint should be considered

In addition to the equipment listed above, medications are often also part of a first aid kit. This component is commonly referred to as the 'rucksack pharmacy'.

For the rucksack pharmacy, a distinction should generally be made between those medications required for personal, long-term use (e.g. antihypertensives, lipid-lowering agents, anti-diabetics) and those intended for the treatment of acute symptoms (e.g. headache, diarrhoea). The administration of medication to others is generally not recommended and may be illegal unless a qualified person is present. Contraindications, incorrect dosing, drug interactions and allergic reactions are difficult for laypersons to assess and manage. This significantly increases the risk of an adverse event. It is therefore all the more important that each participant in an alpine activity takes responsibility and equips their own rucksack pharmacy with all the medications they personally require and are familiar with.

The following applies to the rucksack pharmacy:
- The packaging should be as pressure-resistant as possible.
- The contents should be resistant to heat and cold and stored at room temperature outside of expeditions.
- Medications (e.g. tablets, suppositories, ampoules) can be packed in blisters without the outer box, but ideally with the accompanying medication information leaflet.
- The expiry date of medications should be checked regularly.
- Used materials should be replaced promptly after the end of each outing.

It is difficult to define which medications should be included in the extended medical kit of medically-trained individuals. In general, only those medications with which the user is familiar in terms of their pharmacological profile should be carried.

A common challenge is the management of trauma-related pain.

Recent developments have significantly expanded the range of medications available for the treatment of moderate to severe pain. The management of severe pain is no longer necessarily dependent on establishing a peripheral intravenous line, as alternative routes of administration for potent analgesics have become available for acute pain management.

In principle, the use of potent analgesics should be part of daily clinical practice in order to ensure competence in giving these drugs in the challenging alpine environment.

For the treatment of moderate to severe pain, the substances available intravenously in Central Europe are piritramide, morphine and fentanyl (acting on opioid receptors) and ketamine (acting primarily on NMDA receptors). Alternatives include orodispersible tablets administered buccally (via the oral mucosa) or nasal sprays administered intranasally.

Recommendations for additional medications that could be carried are largely based on the planned alpine activity (Townes 2002; Gross 2016; Brandenburg and Locke 2017). All medications required for the management of life-threatening emergencies are considered essential; all other substances can be selected according to the specific alpine activity.

Which medications and medication groups should be included (◘ Table 40.1)?

The administration of intravenous medications requires the availability of a tourniquet, disinfectant, intravenous cannulas, syringes of various sizes, drawing-up needles, and a sharps disposal box.

◘ **Table 40.1** Medications and medication groups[a] that can be included in the medical kit

Medications and medication groups	Formulation	Indication(s)
Adrenaline (epinephrine)	Intravenous/intramuscular	Cardiorespiratory arrest, anaphylaxis (i.v. or i.m.)
Antiarrhythmics: amiodarone or lidocaine	Intravenous	Cardiorespiratory arrest
Antihistamines	Topical or systemic	Anaphylactic reaction, allergic reaction
Glucocorticoids	Intravenous or oral	Anaphylactic reaction, altitude-related illness
Opioids	Intravenous, intranasal or oral	Pain management
Ketamine	Intravenous, intranasal	Pain management
NSAIDs	Oral, topical	Pain management, anti-inflammatory
Benzodiazepine	Intravenous, intranasal	Sedation when administering NMDA receptor antagonists, cerebral seizure
Local anaesthetic	Topical	Wound care, local infiltration therapy

(continued)

Table 40.1 (continued)

Medications and medication groups	**Formulation**	**Indication(s)**
Low-molecular-weight heparin	Subcutaneous	Thromboprophylaxis, acute coronary syndrome
Acetylsalicylic acid	Intravenous or oral	Acute coronary syndrome
Proton pump inhibitor	Oral	Abdominal complaints
Antiemetic	Intravenous or oral	Nausea, vomiting
Broad-spectrum antibiotic	Oral	Bacterial infections
Antiviral agent (aciclovir)	Oral, topical	Viral infections
Bronchodilator metered-dose inhalers	Inhalation	Respiratory tract infections
Nasal spray	Nasal	Upper respiratory tract infection
Antibiotic eye ointment/drops	Topical	Conjunctivitis, hordeolum
Carbonic anhydrase inhibitor (acetazolamide)	Oral	Altitude-related illness
Calcium channel blocker (nifedipine)	Oral	Altitude-related illness

[a] Due to the frequent changes in brand names, only drugs and drug classes are listed
NSAIDs non-steroidal anti-inflammatory drugs, *i.m.* intramuscular, *i.v.* intravenous

40.5 Alpine Emergency: Alerting and Localisation

If it becomes necessary to request assistance due to an alpine emergency or a medical incident, the technical means for doing so have advanced rapidly in recent years. The alpine distress signal now appears almost antiquated. Nevertheless, it should be mentioned, as it can sometimes be lifesaving. Using an appropriate device (e.g. whistle, mirror, light source), a visual or acoustic signal is emitted. The sequence consists of six signals given within 1 min. After a one-minute pause, the distress signal is repeated until a response is received, consisting of three signals per minute as confirmation (see ◘ Fig. 40.1). Knowledge of this alpine distress signal is widespread, as mountain rescue services are repeatedly alerted—especially at dusk—due to suspected sightings of such signals.

Apart from the most remote locations, continuous mobile phone coverage is now standard in most tourist regions. It is therefore always advisable to carry a mobile phone for alpine activities, ensuring it is charged, readily accessible and protected against falls.

40.5.1 Alerting

Alerting can be carried out by a conventional call to the well-known and Europe-wide standard emergency number 112 (the standard emergency number in the European Union and many other countries around the

	Minute 1	Minute 2	Minute 3	Minute 4	Minute 5	And so on
Emergency signal	------	Pause	------	Pause	------	And so on
Reply	- - -	Pause	- - -	Pause	- - -	And so on

Fig. 40.1 Schematic of the alpine distress signal. (From Huber et al. 2022)

world) or via the mountain emergency number valid in the respective country. The international emergency number 112 is received at the control centres of the police, who then forward the collected information to the relevant institutions (e.g. ambulance service control centre).

The unique feature of the international emergency number 112 is its independence from the respective network operator, so that if there is no network coverage from the user's own provider, the call is automatically switched to an available GSM network to establish a connection. An emergency call can also be made without entering the PIN code. In addition, location data (Advanced Mobile Location, AML) is now automatically transmitted to the control centre. This enables precise localisation.

How to Alert Emergency Services via 112?

If the reception is poor, it may help to switch the mobile phone off and on again

Do not enter the PIN code

Dial 112 and press the call button

There are several pieces of information that are mandatory in every emergency call:

- **Where** did it happen? Provide the exact location of the incident, ideally with coordinates and the prevailing weather conditions.
- **What** happened? A description of the emergency.
- **How many** people affected? State the number of casualties or people in distress.
- **What type** of illness or injuries? Describe particularly any life-threatening conditions.
- **Who** is reporting the incident? Give your name and a call-back number.

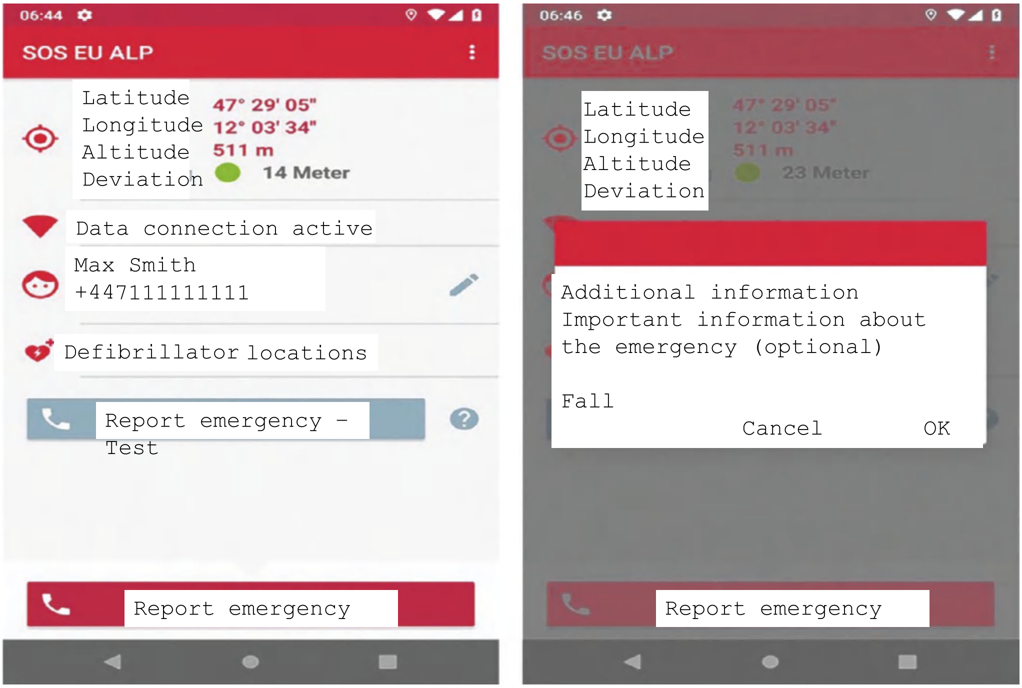
The emergency call is always ended by the dispatcher once all necessary details have been obtained. Increasingly, dispatchers now provide medical support in the form of simple first aid instructions over the phone. This helps callers to remain calm and take effective action in exceptional situations.

40.5.2 Location and Mobile Phone Tracking

Due to the continuous registration in the mobile network, a mobile phone can be located within certain limits by the operator of the GSM network. If a call is made or data is transmitted (SMS, MMS), the location can be determined more precisely than in standby mode.

In the recent past, the best a mobile network operator could do was to narrow down the sender's location using receiver antennae information. However, precise pinpointing, as would be necessary for efficient person localisation, is often not possible in rough, alpine terrain where the number of receivers is limited.

A proven and now widely used alternative is to use emergency apps on smartphones or smartwatches. Here, the request for assistance—or more precisely, the connection to the emergency control centre—is primarily established via an application, which also transmits the exact GPS coordinates. A data connection is required for this. This generally allows for precise localisation of the caller and has proven highly effective in the daily operations of alpine rescue services. It eliminates the need for repeated calls with the informant to determine the exact location. Examples include in the German-speaking European Alpine countries the 'SOS EU Alp' and 'Rettung' apps, as well as other 'Emergency' apps in other mountain areas, which offer these functions (◘ Figs. 40.2 and 40.3).



Latitude 47° 29' 05"
Longitude 12° 03' 34"
Altitude 511 m
Deviation ● 14 Meter

Data connection active

Max Smith
+447111111111

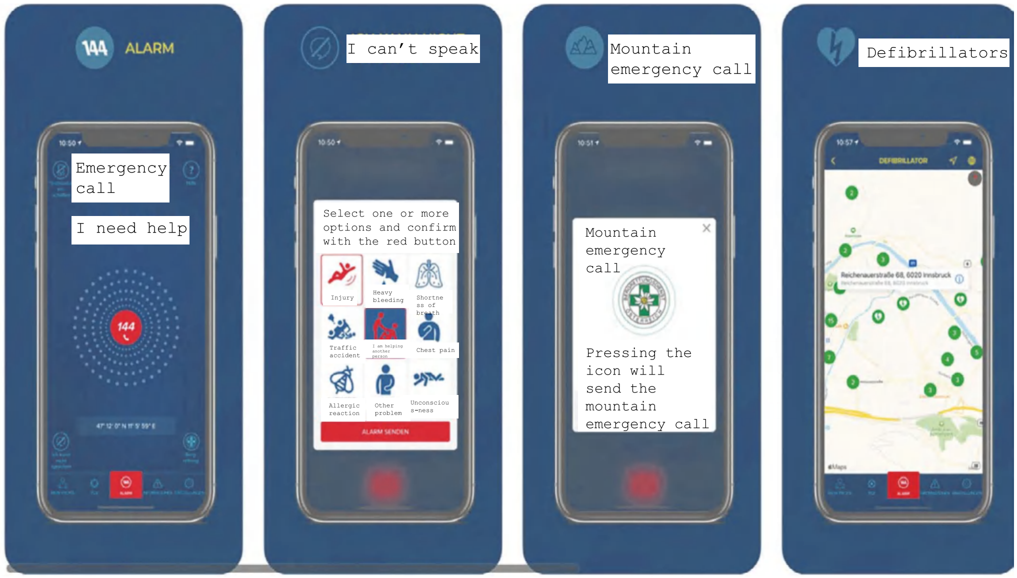
Defibrillator locations

Latitude 47° 29' 05"
Longitude 12° 03' 34"
Altitude 511 m
Deviation ● 23 Meter

Additional information
Important information about the emergency (optional)

Fall

◘ **Fig. 40.2** Digital application 'SOS EU ALP'. (Source: ► https://www.chip.de/downloads/SOS-EU-ALP-Android-App_173198272.html, accessed: 19.09.2023)


144 ALARM
Emergency call
I need help
144
I can't speak
Injury
Heavy bleeding
Shortness of breath
Traffic accident
I am helping another person
Chest pain
Allergic reaction
Other problem
Unconsciousness
ALARM SENDEN
Mountain emergency call
Defibrillators
DEFIBRILLATOR
Reichenauerstraße 68, 6020 Innsbruck

Select one or more options and confirm with the red button

Mountain emergency call

Pressing the icon will send the mountain emergency call

Fig. 40.3 Digital application 'Rettung'. (Source: ► https://apps.apple.com/at/app/rettung/id1285452790, accessed: 19.09.2023)

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Altitude Medicine Miscellaneous

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Pregnancy and Contraception at High Altitude

Beata Seeber, Bettina Böttcher, and Evelyn Baumgartner

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41.1 Exercise and Pregnancy

During pregnancy, cardiac output, stroke volume, and heart rate increase. In contrast, women who continue aerobic exercise during pregnancy have a lower resting heart rate, greater stroke volume, and higher maximal oxygen uptake compared to physically inactive pregnant women (O'Toole 2003; Pivarnik et al. 1993). Exercise capacity during weight-bearing activities, such as treadmill exercise, is already increased in athletic women at the beginning of pregnancy (Clapp 3rd 1989; Lotgering et al. 1985) and is maintained throughout pregnancy. High-performance exercise in pregnant women has an additional positive training effect which is reflected by a significant increase in maximal oxygen uptake after pregnancy (Clapp 3rd and Capeless 1991; Kardel 2005).

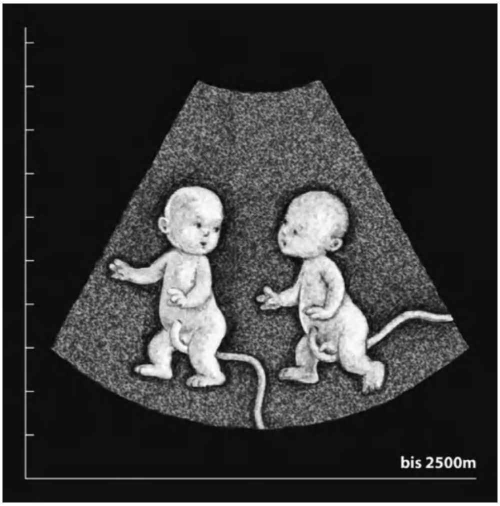
The current recommendations of the American College of Obstetricians and Gynecologists (ACOG) (ACOG 2020; Artal 2016), the Society of Obstetricians and Gynaecologists of Canada (SOGC) and the Canadian Society of Exercise Physiology (CSEP) (Mottola et al. 2018) are as follows: women with uncomplicated pregnancies and no health restrictions should engage in at least 30 min of moderate exercise daily (Artal and O'Toole 2003). Women who did not exercise prior to pregnancy should start with 15 min three times per week and gradually increase the frequency and duration of physical activity. Achieving maximal fitness is not the goal (Davies et al. 2003).

According to ACOG, pregnant women living at sea level can safely exercise at altitudes up to 1829 m, and pregnant women residing at higher altitudes may also be able to exercise safely above this level. The Canadian guidelines note that it appears safe for acclimatised pregnant women to exercise at moderate intensity at altitudes of 1800–2500 m, but that exercise above 2500 m should be avoided.

Sports with a high risk of injury, such as climbing and skiing, should generally be avoided. Recommended activities are those with controlled movements, such as hiking, cycling, swimming and water aerobics. The risk of falls and trauma is particularly increased in the second half of pregnancy, as the centre of gravity shifts and joints become laxer due to hormonal changes. Falls carry a potential risk of placental abruption, which can result in intrauterine foetal death.

The talk test is the simplest way to avoid overexertion; if verbal conversation is possible during exercise, the intensity remains within the aerobic range and does not overburden the pregnant woman (Wolfe and Davies 2003; ◘ Fig. 41.1).

◘ Table 41.1 serves as a reference for the altitude ranges mentioned in the text. Further information on altitude categories can be found in ► Chap. 4.



◘ **Fig. 41.1** Indirect monitoring of maximal exercise intensity assessed by the talk test. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission from Peter Plattner)

Table 41.1 Classification of altitude levels in mountaineering. (Roach et al. 2016)

Moderate altitude	1500–3500 m
High altitude	3500–5500 m
Extreme altitude	5500–8848 m

Exercise Recommendations for Pregnant Women

- Aim for 30 min of moderate exercise per day
- Avoid sports with a high risk of injury
- Monitor physical exertion using the talk test (see Fig. 41.1)

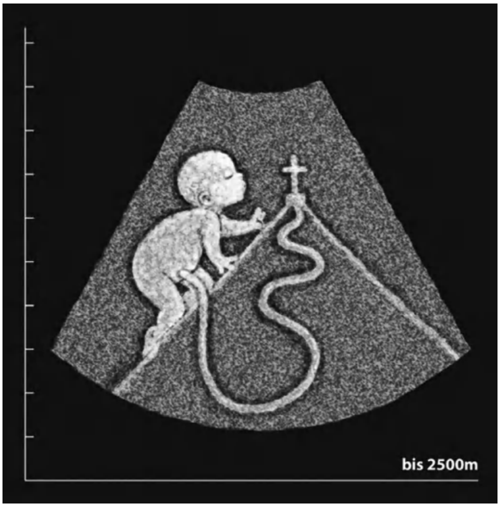


Fig. 41.2 Moderate mountaineering is possible in uncomplicated pregnancies. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission from Peter Plattner)

41.2 Altitude and Pregnancy

In principle, the guidelines mentioned above are also applicable to mountaineering during pregnancy. The Society of Obstetricians and Gynaecologists of Canada (SOGC) and the Canadian Society of Exercise Physiology (CSEP) consider light physical activity in pregnant women between 1500 and 2500 m to be safe for both mother and child (Mottola et al. 2018) (see Fig. 41.2).

Due to a lack of research data, it is unclear whether it is entirely safe for pregnant women to exercise at altitudes of 2500–5300 m. Most studies on the effects of high altitude on mother and child have been conducted with women who already lived at these altitudes prior to pregnancy. By contrast, there is virtually no data on pregnant women who spent only a limited period of their pregnancy at altitudes above 2500 m.

Furthermore, there are few studies evaluating pregnant women engaging in mountain sports, and none at all for altitudes above 2228 m. In addition, the few available studies have notable methodological limitations such as very small sample sizes (e.g. n = 7–12) or very short periods of exertion (e.g. 3–12 min).

Keyes et al. (2016) conducted an online survey among women in Colorado who had experienced at least one pregnancy. Notable findings included the prevalence of exposure to high altitudes (>2440 m) during pregnancy, as well as pregnancy and perinatal complications. The rates of miscarriage and most other pregnancy complications were similar in pregnancies with and without exposure to altitudes above 2440 m. There was some evidence that women living at low altitude who travel to high altitude may have a higher risk of preterm labour, and that infants born to women who spent time at high altitude may have a higher oxygen requirement at birth. However, the authors noted limitations in their results due to the retrospective study design, recall bias, and a relatively small sample (459) of women. They also found that although more than half of pregnant women travelled to high altitudes, only 25% received medical advice regarding altitude, including a small proportion (3%) who were advised not to ascend above 2440 m (Keyes et al. 2016). This highlights the importance of physicians being familiar with guidelines for altitude exposure during pregnancy so that they can advise women appropriately.

41.2.1 Cardiopulmonary and Physiological Changes at High Altitude

Cardiopulmonary adaptation during pregnancy in women living at high altitude is like that at moderate altitude. However, the increases in heart rate, stroke volume, and blood volume are less pronounced (Kametas et al. 2004), and the rise in blood flow in the uterine arteries is also reduced (Julian et al. 2009). The ratio of placental size to foetal size is shifted towards the placenta in pregnancies at high altitude, which enables improved placental-foetal exchange. However, hypoxic respiratory alkalosis at high altitude cannot be fully compensated by renal bicarbonate excretion (Bobrowski 2010).

According to the Medical Commission of the Union Internationale des Associations D'Alpinisme (UIAA MedCom), pregnant women respond to reaching a certain altitude with an immediate increase in respiratory rate and cardiac output, resulting in a parallel increase in blood flow in the uterine artery and placental perfusion. This physiological response ensures that foetal oxygen supply is not significantly impaired (Jean et al. 2005). After acclimatising for 2–3 days, physical activity within the safe aerobic range is possible.

Acute mountain sickness can, of course, also affect pregnant women if acclimatisation is inadequate. However, its prevalence appears to be lower in pregnant women, likely because of pregnancy-induced hyperventilation (Niermeyer 1999). It is important to note that acetazolamide is contraindicated during the first 3 months of pregnancy due to teratogenic risk, and it may cause neonatal jaundice if given after the 36th week of pregnancy (Jean et al. 2005).

The very dry air at high altitude and pregnancy-induced hyperventilation can lead to maternal dehydration. It is particularly important for pregnant women to maintain adequate hydration.

41.2.2 Effects of High-Altitude Exposure on Fertility and Early Pregnancy

Possible negative effects of high altitude on follicular maturation, subsequent fertilisation, and embryonic development have not yet been comprehensively studied. Xiong et al. (2023) compared in vitro fertilisation (IVF) parameters in women living in a normoxic environment below 500 m with those of women living in a high-altitude hypoxic environment. They showed that women at higher altitudes required higher doses of gonadotropins over a longer stimulation period for assisted reproduction, tended to have lower fertilisation rates and reduced embryo development to the blastocyst stage and had fewer usable high-quality blastocysts. Wu et al. (2022) reported a live birth rate of 35% with subsequent frozen embryo transfer in high-altitude regions (>3650 m) is roughly comparable to rates at lower altitudes. These data suggest that altitude may have certain effects on the female reproductive system as well as on the onset of pregnancy. However, further studies are needed before any conclusions can be drawn.

In the first half of pregnancy, the risk associated with high-altitude exposure appears to be low. There is no clear evidence that women who travel to or reside in high-altitude regions have a higher rate of early pregnancy loss. However, since most miscarriages occur in the first trimester, it is advisable for women who have had difficulty conceiving or who are otherwise at risk for miscarriage or early pregnancy complications to avoid travel to high altitudes.

41.2.3 Negative Effects of High Altitude on Advanced Pregnancy

In general, pregnancy at high altitude leads to relative intrauterine growth restriction, resulting in neonates with lower birth weights (LBW) (Lithy et al. 1975). On average, birth weight decreases by 100 g per 1000 m of altitude. This effect is probably mainly due to chronic hypoxaemia (Giussani et al. 2001; Jensen and Moore 1997) and can be observed starting at about 1500 m, but becomes more pronounced above 2500 m (Yip 1987). In populations that have lived at high altitude for many generations (e.g. Ethiopians and Tibetans), the reduction in birth weight is only half as great as in genetically non-adapted women (Moore 2001; Moore et al. 2011). Other complications such as pregnancy-induced hypertension and pre-eclampsia, along with associated complications such as premature placental abruption occur three times more frequently at high altitudes (Moore et al. 1982; Palmer et al. 1999). Accordingly, maternal, foetal, and neonatal morbidity and mortality also increase.

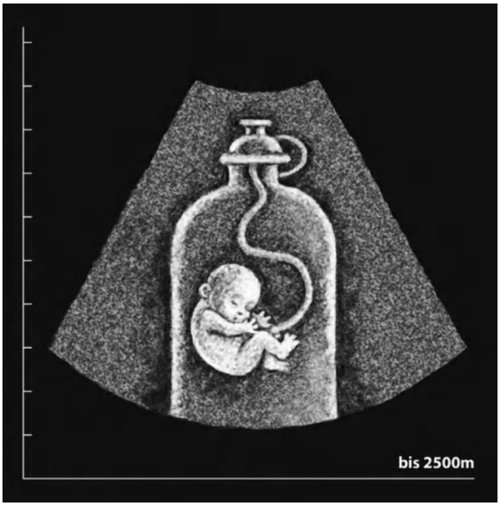
Various other complications associated with pregnancy at high altitude including increased blood loss during delivery, a higher incidence of placenta praevia, polyhydramnios, premature rupture of membranes and preterm birth have been described, but have not yet been sufficiently substantiated. As stated above, it remains unclear whether miscarriages are more common at high altitude. Indirect evidence may be extrapolated from reports of an increased risk of miscarriage among flight attendants, although these studies have significant methodological limitations (Magann et al. 2010).

Absolute Contraindications for Stays at High Altitude During Pregnancy

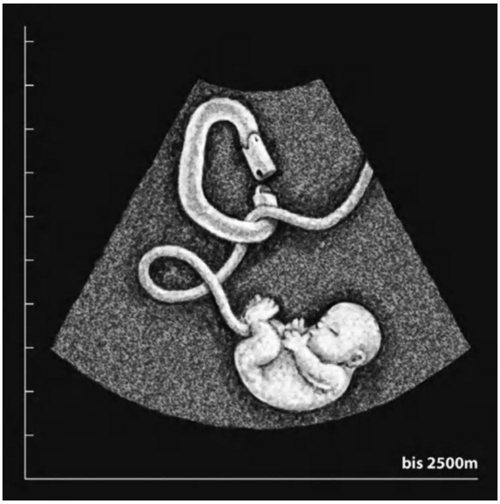
- Anaemia
- Arterial hypertension
- Intrauterine growth restriction (IUGR)
- Cardiac or pulmonary disease
- Nicotine abuse
- Placental insufficiency
- Pre-eclampsia

41.2.4 Mountaineering at High and Extreme Altitudes

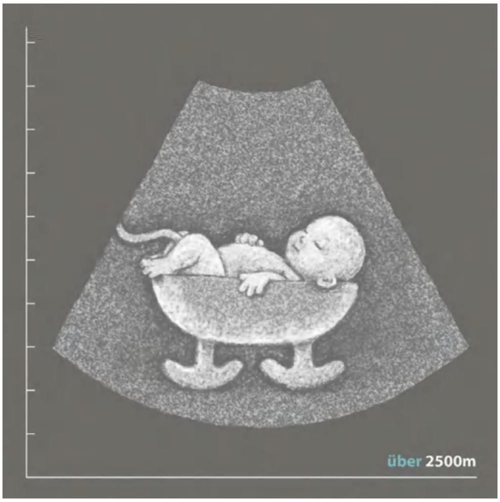
To date, there are no data on pregnancy and mountaineering at high and extreme altitudes. Recommendations are therefore based solely on expert opinion (■ Figs. 41.3 and 41.4). For example, some authors take a restrictive view and generally advise against



■ **Fig. 41.3** Adequate fluid intake must be ensured. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)



■ **Fig. 41.4** Mountain sports with a high risk of injury should be avoided. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)



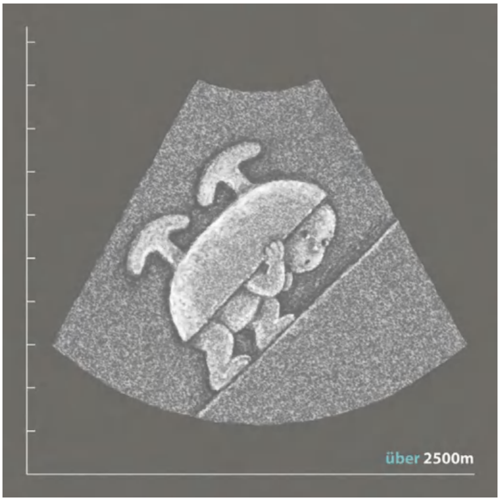
■ **Fig. 41.5** After 2–3 days of acclimatisation, physical activity within a safe aerobic range is possible. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

mountain sports during pregnancy above 1600 m, as there are no reliable data (Entin and Coffin 2004). Other authors have issued recommendations for altitudes above 2500 m (Huch 1996; Jean et al. 2005; Jean and Moore 2012; Wolfe and Davies 2003) (■ Figs. 41.5 and 41.6).

Mountaineering During Pregnancy

At moderate altitudes:

- Moderate mountaineering is possible in uncomplicated pregnancies; simple monitoring of exertion is advisable (e.g. using the talk test).
- Adequate fluid intake should be ensured.
- All mountain sports with a high risk of injury should be avoided.



■ **Fig. 41.6** Strenuous activity is only recommended after 2 weeks of acclimatisation and only at altitudes between 2500 and 3000 m. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission of Peter Plattner)

At altitudes above 2500 m:
- An acclimatisation period is required.
- Moderate aerobic activity is possible once the resting heart rate has returned to baseline.
- Strenuous activity is only recommended after a 2-week acclimatisation period and only at altitudes between 2500 and 3000 m.
- Attention should be paid to symptoms of acute mountain sickness.

41.2.5 Consideration of Additional Risks in Remote High-Altitude Regions

Most high-altitude locations have additional characteristics that must be considered when planning a stay. They are often far from medical care, particularly gynaecological services. Immediate medical attention for problems such as bleeding or infection during pregnancy is therefore not possible. Women planning to travel to high altitudes in early pregnancy should have the intrauterine location of the pregnancy confirmed to avoid unexpected (and potentially life-threatening) complications from an ectopic pregnancy. In high-altitude regions of exotic countries, the risk of contracting an infectious disease such as malaria, hepatitis E or bacterial or viral gastroenteritis is increased. Infected pregnant women may experience complications or even life-threatening problems. Furthermore, certain prophylactic therapies, such as malaria prophylaxis with quinolones and sulphonamides, are contraindicated during pregnancy (Jean et al. 2005).

41.3 Contraception at High Altitude

In principle, all contraceptive methods are suitable for use at high altitude, provided the individual situation and risk profile are taken into consideration. When mountaineering at high altitude, the safety, side effects and reliability of the chosen contraceptive may change. In particular, the significantly increased risk of thromboembolism at high altitude (Anand et al. 2001; Gupta and Ashraf 2012) and various aspects of the handling of each contraceptive method must be considered (see overview in ◘ Table 41.2).

Within the context of natural family planning, based on measurements of body temperature, cervical mucus and cycle length, it should be noted that changes in time and climate zones, as well as physical exertion, cold and weight loss, can more frequently lead to intermenstrual bleeding and altered cycle lengths. This may compromise the reliability of the chosen method.

Hormonal preparations can also be used for cycle regulation, suppression or postponement of menstruation (Keyes 2015).

When using hormonal contraceptives, the increased risk of thrombosis and pulmonary embolism must be considered. Exposure to high altitude while taking hormonal contraceptives increases the risk of developing cerebral venous thrombosis (Kharel et al. 2023). The risk is also two- to sixfold higher during the first 3 months after starting hormonal contraception compared to later use (Lidegaard et al. 2011). Therefore, during this period, additional risk factors such as the inherently increased risk of thrombosis at high altitude, dehydration and cold should be avoided (◘ Figs. 41.7 and 41.8).

Table 41.2 Contraceptive methods and their considerations at high altitude

	Oral combined hormonal contraceptives	Contraceptive ring	Hormonal patch	Oral progesterone-only (Mini-pill)	Hormonal rod/implant	Three-month injection	Hormonal IUS	Copper IUD	Condom	Natural family planning
Application	Daily	Every 3 weeks	Weekly	Daily	Every 3–5 years	Every 3 months	Every 3–8 years	Every 3–5 years	Each time before intercourse	Daily temperature measurement, cervical mucus
Special considerations	Cycle regulation possible Extended cycle “off-label” → absence of menstruation	Cycle regulation possible Extended cycle “off-label” → absence of menstruation	Unsuitable in cases of heavy sweating or high humidity		May cause discomfort in the upper arm Long-term contraception	Must be administered intramuscularly by a healthcare professional	Secure placement, long-term contraception	Frequent heavy bleeding	Protection against sexually transmitted infections	Requires a regular daily routine Method must be practised, requires good compliance

Possible issues	Reduced efficacy in case of gastrointestinal infections/certain antibiotic use At altitudes above 4500 m, administration should be critically reconsidered (risk of thrombosis)			Intermenstrual bleeding, spotting Reduced efficacy in case of gastrointestinal infections/antibiotic use		Decrease in bone mineral density with long-term use	Intermenstrual bleeding		Failure due to breakage or displacement; emergency contraception (“morning-after pill”) recommended as backup	
Risk of thrombosis	Increased	Increased	Increased	Low	Low	Low	Low	Low		
Travel compatibility	Store protected from heat and consider time zone changes Reserve medication	Store protected from heat Reserve medication	Store protected from heat and consider time zone changes Reserve medication	Store protected from heat and consider time zone changes Reserve medication	Yes	(Yes)	Yes	Yes	Store protected from heat	Not suitable for travel to different time and climate zones; cycle irregularities may occur due to exertion or cold

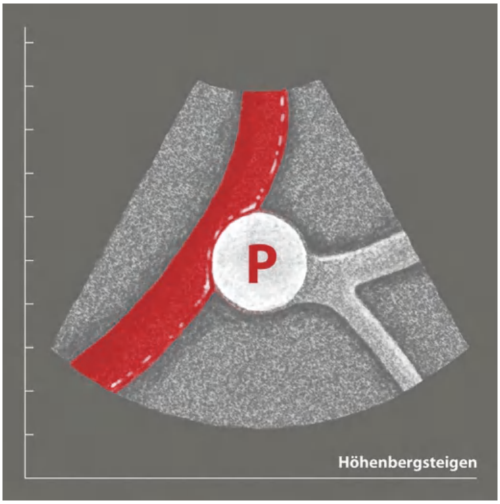


Fig. 41.7 The risk of thrombosis remains twice as high compared to the period before starting the pill. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission from Peter Plattner)

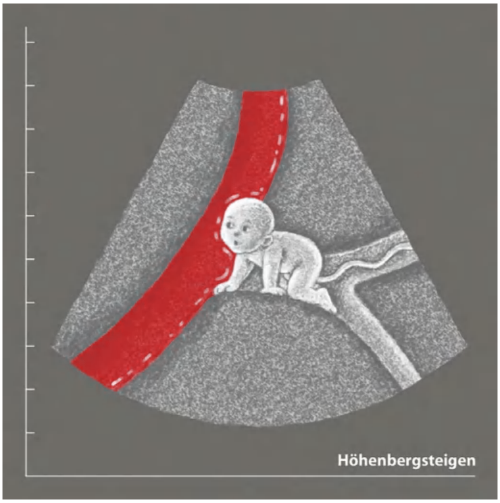


Fig. 41.8 Pregnancy increases the risk of thrombosis fivefold. (Illustration by Lisa Manneh for the Austrian Alpine Club, with kind permission from Peter Plattner)

Altogether, in the absence of additional risk factors such as a genetic risk of thromboembolism, pre-existing cardiovascular disease or nicotine abuse, the use of combined hormonal preparations is considered safe up to an altitude of 4500 m as it is at sea level. For stays above 4500 m lasting more than 1 week, the International Climbing and Mountaineering Federation (UACC) and the Faculty of Sexuality and Reproductive Healthcare (FSRH) recommend a critical assessment of the use of hormonal preparations (Hillebrandt and Meijer 2009).

In the event of altitude sickness, the risk of thrombosis may be further increased by polycythaemia and dehydration due to vomiting and limited water availability (Cheng et al. 2009).

Combined preparations containing both oestrogen and progestogen carry a higher risk of thromboembolism than progestogen-only preparations. Progestogen-only preparations may cause breakthrough bleeding as an adverse effect, which can be particularly inconvenient during trekking or when staying in remote areas. These aspects should be considered when providing contraceptive counselling to female mountaineers. For those seeking long-term contraception, intrauterine devices such as the copper IUD or hormonal IUS, or the contraceptive implant, represent good options. It is advisable to establish the chosen method of contraception several months prior to departure and, in the case of oral preparations, to bring a sufficient supply of medication for the duration of the trip.

Additionally, it should be considered that travel may increase the risk of gastroenteritis, which can compromise the reliability of oral hormonal contraceptives. The same principle applies to the use of certain antibiotics.

When taking oral preparations regularly, time zone differences must be considered. Condoms are the only contraceptive method that provides protection against sexually transmitted infections. It should be noted that exposure to high temperatures can impair the integrity of latex.

41.3.1 Influence of Hormones on Acclimatisation

Progesterone can influence the development of acute mountain sickness through several mechanisms. Progesterone has antidiuretic properties, acts to relax smooth muscle and can stimulate respiration. In a study involving 50 female participants who ascended from sea level to 3200 m in less than 4 h, it was observed that women using hormonal contraception, and thus had lower progesterone levels, experienced mountain sickness and arterial hypertension more frequently (Harrison et al. 2013). However, these findings were not confirmed in a much larger study, which found no difference in the incidence of mountain sickness between women before and after menopause or among those using hormonal contraceptives (Richalet et al. 2020).

Furthermore, the phase of the menstrual cycle—the follicular phase with low progesterone levels versus the luteal phase with significantly higher progesterone levels—appears to have no effect on respiratory acclimatisation (Muza et al. 1985; Keyes 2015) nor on the occurrence of mountain sickness (Keyes 2015). Prophylactic administration of medroxyprogesterone acetate did not reduce the incidence of mountain sickness in either women or men (Wright et al. 2004).

Although hormonal influences on respiration are well documented, the evidence regarding the effects of hormonal status, menstrual cycle phase, or the use of hormonal preparations on acclimatisation at altitude or on mountain sickness remains very limited.

Conclusion

- Pregnant women benefit from regular physical activity. Reduced or absent physical activity increases the risk of obesity, gestational diabetes and hypertensive pregnancy disorders, including pre-eclampsia. Consequential negative outcomes for both mother and child would be expected.
- Mountain sports, including moderate mountaineering, up to an altitude of 2500 m during uncomplicated pregnancies, can be recommended if indirect monitoring of maximum exertion using the talk test and adequate fluid intake is monitored. Mountain sports with a high risk of injury should be avoided.
- Above an altitude of 2500 m, it is additionally recommended to undertake slow acclimatisation. Only after acclimatising for 2–3 days is physical activity in the safe aerobic range advisable. Strenuous exertion should only be undertaken after 2 weeks of acclimatisation and only at altitudes of 2500–3000 m, with attention to symptoms of acute mountain sickness.
- During high-altitude mountaineering, the risk of thromboembolism is increased by various factors such as dehydration, immobilisation due to weather, cold and thrombocythaemia.
- Hormonal contraceptives, especially combined preparations, are inherently associated with an increased risk of thromboembolic events. Progestogen-only preparations, whether oral, as a hormonal intrauterine system, or as an implant, carry a lower risk of thrombosis and may represent a suitable contraceptive option for female high-altitude mountaineers.
- With the above contraceptive methods, the occurrence of menstrual irregularities and spotting should be considered.
- Provided there are no additional risk factors such as thrombophilia, cardiovascular disease or nicotine abuse, hormonal contraceptives can be used at altitudes up to 4500 m.

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42

Specific Aspects of Mountaineering in Children and Adolescents

Susi Kriemler

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Whether or not children should be taken to high altitudes remains a subject of debate, with recommendations ranging from strict warnings to enthusiastic endorsements, depending on whether one has just read about a baby suffering frostbite or has stood atop a 4000-m peak with a 12-year-old son. Over 20 years ago, an international expert group published a consensus statement on altitude sickness in children, for physicians (Pollard et al. 2001). Remarkably little has changed since then, and much of the information remains relevant for all parents and individuals taking children into the mountains. An engaging, more travel medicine-oriented chapter was written by Yaron et al. (2002), which is also well worth reading.

42.1 Physical Characteristics

Children differ from adults in many physiological and psychological aspects. For example, there is a 20-fold difference in body weight between a 3.5 kg infant and a 70 kg adolescent. Accordingly, medication dosages and fluid requirements vary and must be adjusted. If parents do not know their child's weight, this can lead to serious problems when calculating medication doses or fluid replacement in cases such as gastroenteritis with vomiting and diarrhoea.

Thermoregulation in children is less efficient than in adults, which puts them at greater risk in both cold and hot environments. Because children have a greater body surface area relative to their mass or body weight, they equalise temperature differences between their body and the environment more rapidly. As a result, they cool down and overheat more quickly than adults.

In cold conditions, factors such as lower subcutaneous fat and lack of movement—especially in young children who are often carried motionless on their parents' backs—are additional risk factors. In hot conditions, the still immature sweat production before puberty leads to further increases in body temperature. In our latitudes, cold is the predominant problem. In this context, the principle of the wind chill factor must be considered. This simply means that the effect of cold on the skin, or the overall heat loss from the body, is significantly influenced by wind speed. For example, a wind speed of 40 km/h at a temperature of 0 °C results in the same heat loss as in a temperature of −16 °C without wind.

Additionally, heat loss through the skin can increase many times over if the skin is wet, as the thermal conductivity of water is 20–25 times higher than that of air. This often occurs in the mountains when a child has been running around and sweating, or when it is raining or snowing. Dry clothing and spare clothes, especially for areas not primarily exposed (such as damp socks or undershirts), are just as essential on an expedition as wind protection and emergency supplies.

Approximately 80% of lifetime sun exposure occurs before the age of 20, and the risk of developing malignant melanoma is at least twice as high if a child or adolescent has suffered one or more episodes of sunburn. Prevention of sunburn involves the use of sunscreens that protect against both UVA and UVB radiation, or simply covering exposed skin with textiles that are as opaque to light as possible.

Children experience more infections than adults, and these often take a more severe course due to first-time exposure to infectious bacteria or viruses, as well as anatomical differences. Children have narrower 'tubular systems' (e.g. airways, urinary tract), which can become blocked more quickly by inflammation-induced mucus and swelling, and thus become symptomatic more rapidly.

Any type of fever in the preschool age can lead to febrile convulsions, loss of appetite, nausea, vomiting, diarrhoea with dehydration and weakness. Remember that all these symptoms can mimic altitude sickness. Diarrhoea and vomiting are troublesome issues when travelling, especially if they persist for several days. Children dehydrate much more quickly than adults; the absence of urine for more than 6 h is a simple diagnostic indicator of dehydration. In such situations, it is important to ensure that the child is more or less compelled to take in fluids in small sips over several hours, even if they refuse or continue to vomit. Sensible parents carry appropriate treatments for every possible illness to avert disaster in such situations. If symptoms do not resolve within a few hours, help must be sought and, in the case of altitude exposure, descent is necessary.

It is particularly important in mountain sports with children not to spoil their enjoyment of nature and physical activity. This includes an age-appropriate itinerary tailored to the children's physical and psychological capacities. Everything should be playful. Younger children are experts at exploring their surroundings. It is helpful to check the area for toxic plants, which can quickly end up in children's mouths, or to attach a bell to their shoes so that the little explorers can be located at any time. Older children are enthusiastic learners when it comes to practising emergency situations, bivouacking, thermal protection or navigation. Let your imagination run free and think back to your own childhood!

Every child is proud to carry their own rucksack. This should not exceed 20% of their body weight. In general, children should not be physically or psychologically overburdened. Any episode of fear may later lead to withdrawal from this unique activity. Children under 12 years of age should not be responsible for belaying a rope partner unsupervised, as they do not yet have a sufficient sense of responsibility.

In all adventures, an emergency plan should be drawn up. This should include local rescue options, an emergency medical kit, and information on the quickest route of retreat. Only those who are well prepared and attentive will remain safe.

Key Points for Trekking with Children

- Adjust the pace and distance of the trek to the children's abilities
- Record the children's body weights
- Take an emergency medical kit (discussed with the family doctor, including medication for the treatment of altitude illness)
- Prepare a rescue plan in case of serious accidents or illness

42.2 Altitude

42.2.1 General Considerations

Even today, there are very few scientific studies addressing the temporary, relatively short-term exposure of children to altitude. Many recommendations are derived from research in adults and have not been directly studied in children.

Altitude can trigger three different acute disorders or diseases in the human body, the clinical presentations of which are described in detail in subsequent chapters of this book:

- Acute mountain sickness (AMS) (see ► Chap. 7),
- High altitude pulmonary oedema (HAPE) (see ► Chap. 9),
- High altitude cerebral oedema (HACE) (see ► Chap. 8).

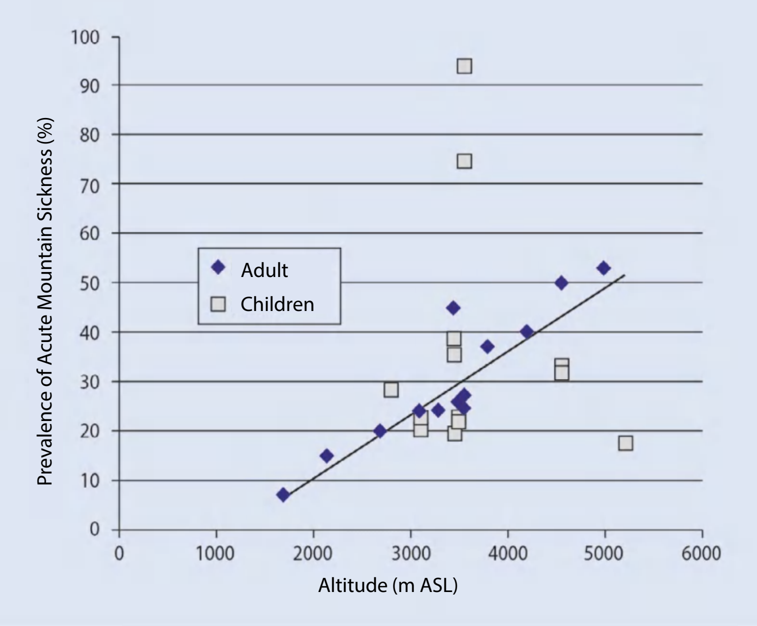
42.2.2 Acute Mountain Sickness

Worldwide, several thousand children travel to altitudes above 2500 m, where acute mountain sickness can affect people of any age. The literature on altitude illness in children is sparse, and population-based data are entirely lacking. ◘ Figure 42.1 provides an overview of the prevalence rates of AMS (Lake Louise Score of 3 or higher) in children and adults at various altitudes. Both generations generally show a similar pattern, with a linear increase in AMS prevalence with increasing altitude, although variability is significantly greater in children. Compared to adults, children are, depending on the study, more (Moraga et al. 2002), equally (Yaron et al. 1998, 2002; Pollard et al. 1998) or less affected.

Older children exhibit the same signs of altitude sickness as adults. As in adults, symptoms typically begin 4–48 h after ascent to higher altitudes. In younger children, the onset of altitude sickness can be difficult to detect, as children under approximately 8 years of age are unable to report symptoms specifically; their statements do not always accurately reflect their actual condition. For this reason, a specially adapted scoring system ('Lake Louise Score for preverbal children', Yaron et al. 2002) (◘ Fig. 42.2) was developed for young children without language skills (up to 3 years of age), which is based on signs of fussiness, loss of appetite, reduced play activity and sleep disturbances.

Of course, many other conditions may be responsible for so-called altitude symptoms. These include motion sickness; lack of motivation; overexertion; any type of infection; poisoning from berries, plants or mushrooms; or inhalation of a small foreign body, which may be misinterpreted as high-altitude pulmonary oedema. In general, any symptom or behavioural abnormality, especially in young children, occurring at altitudes above approximately 2500 m should be considered as altitude sickness and should prompt descent. ◘ Figure 42.3 provides information on the distribution of symptoms of acute mountain sickness in prepubertal children, adolescents and adults after passive ascent to an altitude of 3450 m.

At this altitude, AMS is usually mild and symptoms decrease with increasing duration of exposure (Bloch et al. 2009; Kriemler et al. 2014). Considering the distribution of altitude symptoms, prepubertal children,



◘ **Fig. 42.1** Prevalence of altitude sickness in adults and children. Both groups show a linear increase in prevalence with increasing altitude, with much greater variability observed in children

Materials from Chapter 8 Special features of mountaineering for children and young people, Susi Kriemler

Worksheet 1	Lake Louise Score	Page 1

Lake Louise Score for preschool children up to 3 years

The score is calculated from the sum of the fussiness score (FS) and the paediatric symptom score (PSS). Restlessness is defined as a state of irritability without any clearly identifiable cause lasting at least 2 hours. A diagnosis of altitude sickness is likely if the fussiness score is at least 4, the symptom score is at least 3 and the total score is therefore at least 7, naturally in the case of acute exposure to altitudes of >2500 metres.

Fussiness Score (sum of extent and intensity)

Extent of unexplained fussiness

0	1	2	3	4	5	6
None			Intermittent			Constant

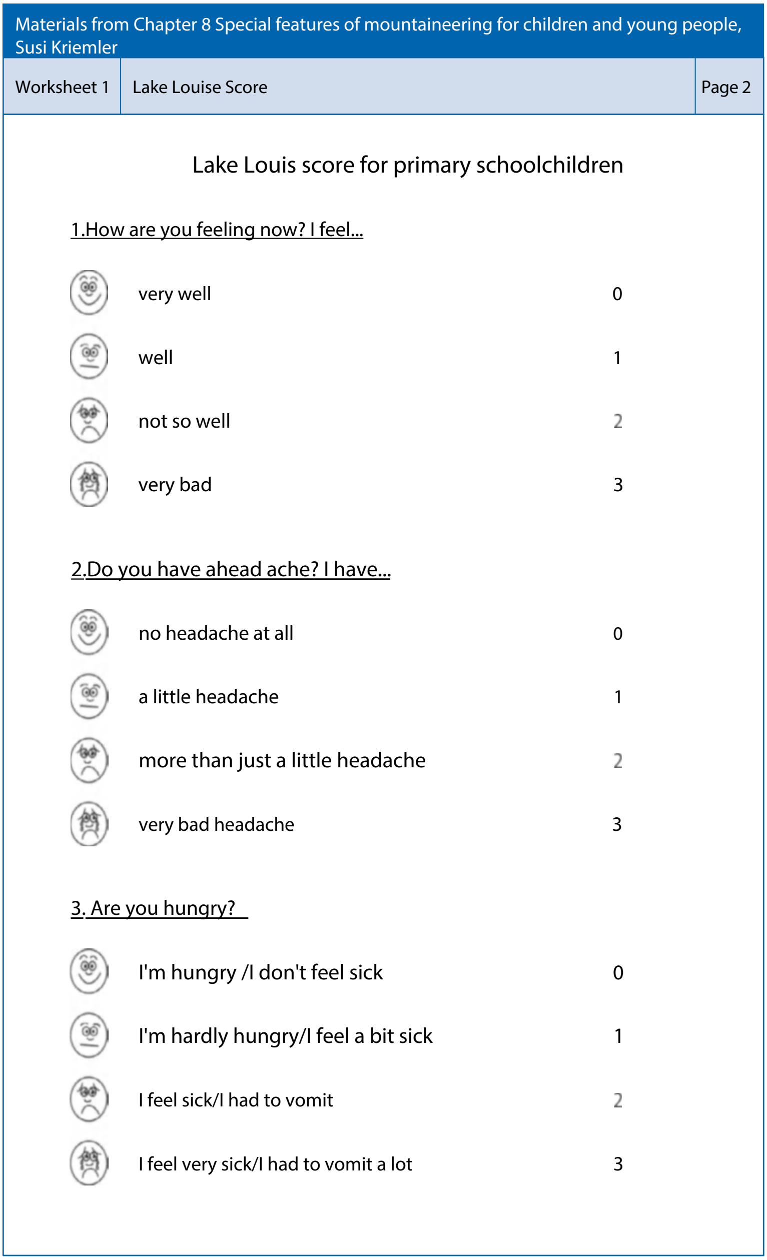
Intensity of unexplained fussiness

0	1	2	3	4	5	6
None			Moderate			Extreme
					Crying	

Child-specific symptom score (= sum of eating, playing and sleeping behaviour)

How well did your child eat today?	0	Normal
	1	Slightly less than normal
	2	Significantly less than normal
	3	Did not eat at all or vomited
How well did your child play today?	0	Normal
	1	Slightly less than normal
	2	significantly less than normal
	3	Did not play at all
How well did your child sleep today?	0	normal
	1	Slightly less than normal
	2	significantly less or more than normal
	3	Could not sleep at all

Fig. 42.2 Lake Louise Score for infants and primary school children. (Adapted from Yaron et al. 2002)



Materials from Chapter 8 Special features of mountaineering for children and young people, Susi Kriemler

Worksheet 1	Lake Louise Score	Page 2

Lake Louis score for primary schoolchildren

1.How are you feeling now? I feel...

very well	0
well	1
not so well	2
very bad	3

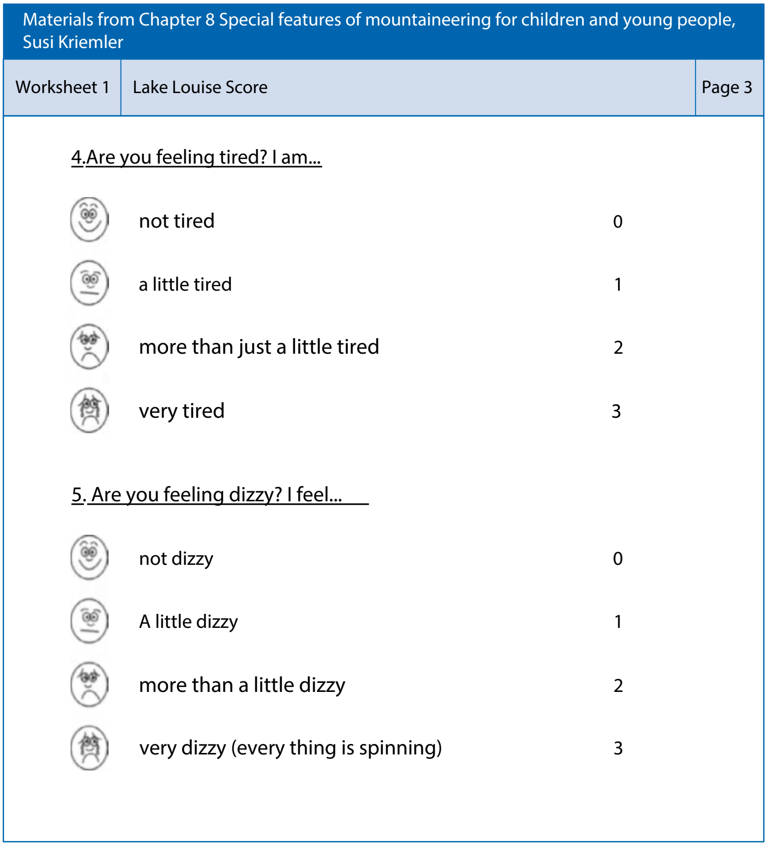
2.Do you have ahead ache? I have...

no headache at all	0
a little headache	1
more than just a little headache	2
very bad headache	3

3. Are you hungry?

I'm hungry /I don't feel sick	0
I'm hardly hungry/I feel a bit sick	1
I feel sick/I had to vomit	2
I feel very sick/I had to vomit a lot	3

Fig. 42.2 (continued)



Materials from Chapter 8 Special features of mountaineering for children and young people, Susi Kriemler

Worksheet 1	Lake Louise Score	Page 3

4.Are you feeling tired? I am...

not tired	0
a little tired	1
more than just a little tired	2
very tired	3

5. Are you feeling dizzy? I feel...

not dizzy	0
A little dizzy	1
more than a little dizzy	2
very dizzy (every thing is spinning)	3

Fig. 42.2 (continued)

compared to adolescents and adults, experience more gastrointestinal complaints but fewer headaches and fewer sleep disturbances. The latter is readily explained, as children have fewer episodes of sleep apnoea at night and are less likely to be awakened by sighs following apnoeic episodes (Kohler et al. 2008). Since 2018, sleep disturbances have no longer recorded as a symptom of acute mountain sickness, as the symptom is too nonspecific and refers to the previous night, which is often spent at low altitude (Roach et al. 2018).

Severe illness is generally rare at an altitude of 3450 m (Jungfraujoch), but can nevertheless occur, especially if ascent continues to higher elevations. In our study at an altitude of 3450 m, two children (aged 9 and 11) required treatment with dexamethasone at Jungfraujoch due to severe AMS.

The Lake Louise Score (LLS), the most commonly used questionnaire for assessing AMS, can be applied without difficulty in older children and adolescents (Roach et al. 2018). For school-aged children, an adapted version of the adult LLS can be used. This version employs child-friendly language and incorporates smileys to help children more easily describe the severity of their symptoms (see above).

Classic risk factors for the development of AMS in adults include rapid ascent (over 300–500 m/day during acclimatisation), the altitude reached, lack of pre-acclimatisation, individual susceptibility, obesity, migraine and inadequate ventilation during physical

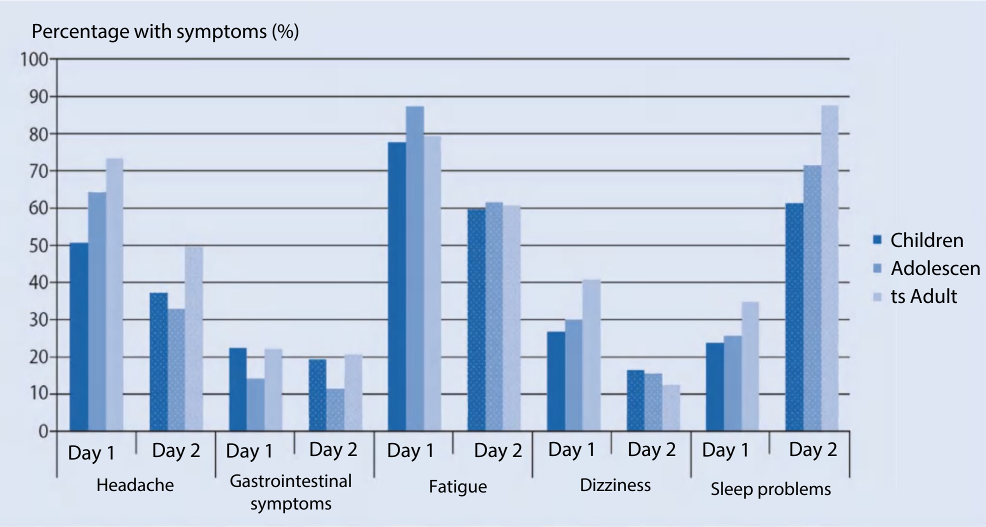


Fig. 42.3 Distribution of symptoms of acute mountain sickness (AMS, y-axis) in prepubertal children, adolescents during puberty, and adults after rapid ascent to 3450 m, 8–12 h and 20–24 h after ascent. (From Kriemler et al. 2014)

exertion in hypoxia. While it can be assumed that these also apply to children, only a few factors have been thoroughly investigated. Most studies show no sex differences. Figure 42.4 illustrates some risk factors in children.

A risk factor for children is their parents. If both parents suffered from AMS at an altitude of 3450 m, the risk for the child to also become ill is five times higher than if both parents remained healthy. In children, rapid passive ascent to high altitude also appears to lead to AMS more frequently than slow, active ascent. While prepubertal children aged 9–12 years are less likely to become ill on the first day at altitude compared to adults, children under 6 years of age are more affected. It should be noted that diagnosing AMS in very young children is extremely challenging. In contrast to adults, a previous episode of AMS does not have predictive value (Rexhaj et al. 2011), although this finding should be interpreted with caution due to the limited data available for children with a history of altitude illness.

42.2.3 High-altitude Pulmonary and Cerebral Oedema

High-altitude pulmonary oedema (HAPE) is a rare condition in the USA and the Alps. A recent review summarised all published cases from 2010 to 2022 (Ucros et al. 2023). The mean age was 9.8 ± 3.6 years, with boys affected 2.6 times more frequently than girls; the occurrence of HAPE in children under 2 years of age was less than 1%; symptoms developed at altitudes between 1500 and 3500 m. Thirty-eight percent of children exhibited classic HAPE (residing below 2000 m and developing HAPE upon ascent), while 58% had so-called re-entry HAPE (residing above 2000 m, developing HAPE upon re-ascent after more than 7 days at lower altitudes, not discussed in this chapter). Fourteen percent of children had a structural heart defect. In other case studies, 28% of children had acute viral infections, mostly of the respiratory tract (Giesenhagen et al. 2019). In the majority of children, symptoms appeared within 24 hours of arrival at altitude. Symptoms included

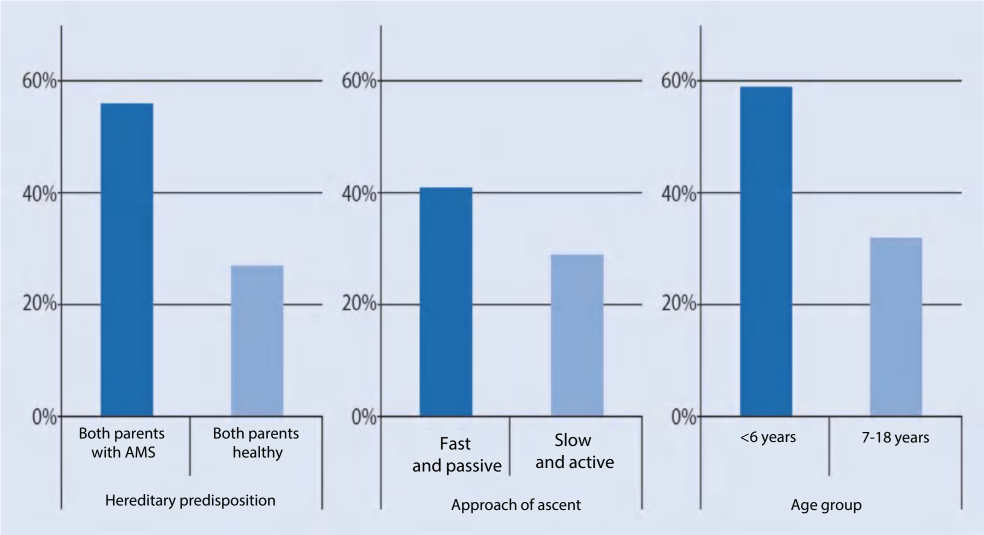


Fig. 42.4 Prevalence of altitude sickness in children and adolescents with and without specific risk factors (y-axis, hereditary predisposition, rate of ascent, age). Children whose parents had previously experienced acute mountain sickness were significantly more likely to develop altitude sickness than children whose parents had not suffered from acute mountain sickness

shortness of breath, cough, vomiting, fever, cyanosis and headache. The presence of headache and vomiting suggests that AMS was also present.

With regard to HACE, there are no published case series, only isolated reports.

Despite the existence of several case studies (Giesenhagen et al. 2019), there are no precise data on the incidence of either high-altitude pulmonary oedema (HAPE) or high-altitude cerebral oedema (HACE) in children. Based on the available data, it can be assumed that HAPE can indeed occur in children. It most commonly develops above 2500 m, but in the presence of (unrecognised) congenital heart defects, it may occur at altitudes as low as 1500 m (which would not be expected based on experience with adult HAPE). It should also be noted that healthy children, especially at the beginning of altitude exposure, develop higher pulmonary arterial pressures than adults (Kriemler et al. 2006), which may fundamentally increase the risk of developing HAPE. Furthermore, it must be emphasised that high-altitude oedemas are life-threatening conditions.

All children and adolescents who develop HAPE anywhere in the world, regardless of altitude, should be evaluated for the following risk factors. These are several situations that represent more or less child-specific risks for the development of HAPE:

- Current or recently resolved respiratory tract infections (such as colds, bronchitis, pneumonia) appear to increase the risk of developing HAPE (Durmowicz et al. 1997). This is, of course, a common situation, particularly in preschool-aged children, and should be taken into account. It is assumed that inflammation in the lung tissue increases the permeability of the pulmonary blood vessels and airways, especially in the context of hypoxia at altitude, resulting in a 'functional leak' and allowing fluid to enter the air spaces.
- Children who experienced impaired pulmonary circulation with hypoxaemia during birth or shortly thereafter have a higher likelihood of developing increased

pulmonary arterial pressure at altitude, and consequently an increased risk of HAPE (Sartori et al. 1999). Although this situation is rare, it can be easily ascertained by asking whether the child required ventilation or oxygen therapy in the first days of life.

- Children with congenital heart defects or chronic lung diseases (e.g. cystic fibrosis), or
- Children with trisomy 21 (Down syndrome) have an increased risk of developing HAPE. In children with trisomy and/or heart defects, HAPE often occurs even at altitudes as low as 1500 m, where it does not usually occur. This is related to the insufficient ability to adapt to the reduced oxygen pressure at high altitude.
- Furthermore, as in adults, a child who has previously experienced HAPE may develop HAPE again with each subsequent ascent to altitude. This assumption is supported by data from children with re-entry HAPE, who, when exposed to altitude/hypoxia, display a risk profile characterised by an excessive rise in pulmonary artery pressure, as has also been documented in adults with recurrent HAPE (Faules et al. 1985).

Risk Factors for the Development of AMS in Children

- Rapid passive ascent
- Altitude reached
- Parents who develop altitude sickness
- Children under 6 years of age

Risk Factors for the Development of HAPE in Children

- Previous episode of HAPE
- Recent or current respiratory tract infections (ears, nose/throat, airways and lungs)
- Children with birth complications resulting in oxygen deficiency (ventilated children, children in incubators)
- Children with congenital heart defects or lung disease
- Probably children of parents with a history of HAPE

42.3 Prevention and Therapy

To prevent travel-related problems in children, general vaccination recommendations and preventive measures, particularly regarding food and drink, should be considered. Information can be found at ► www.safetravel.ch. For the prevention of altitude-related problems in children, three elements are crucial: slow ascent, avoidance of physical overexertion and child-appropriate planning of the activity.

As in adults, it is recommended that above 2500–3000 m, the sleeping altitude should not be increased by more than 300 to a maximum of 500 m per day. For every 1000 m of altitude gained, an additional night at the same altitude should be spent for acclimatisation.

The effect of prophylactic administration of acetazolamide has never been studied in children and should therefore only be considered in exceptional cases and after consultation with a general practitioner. More important is that parents are familiar with the clinical presentation of altitude illnesses and know how their children react while travelling, to distinguish travel-related symptoms from altitude-related symptoms.

Any physical (over-)exertion increases the risk of altitude illness. Whether this is also true for children is not known. Regardless, children should be challenged in an age-appropriate and motivating way so that the enjoyment of trekking is not lost. This includes variety and an attractive daily schedule.

Prevention also includes a detailed medical history for each child and an ‘emergency plan’ in the event of an accident or illness. This involves being fully informed about rescue options and carrying a first aid kit with child-specific medications, including a dosage chart based on body weight or age. If children are present, the possibility of immediate descent with the child should be a prerequisite for any trip.

In the travel first aid kit listed in ▪ Table 42.1, you will find a suggestion for a minimal travel pharmacy suitable for children of all ages. When compiling this, special attention was paid to keeping the volume to a minimum, ensuring the medications can be easily carried and shared, and that their use is multifunctional. The first aid kit must be discussed and prescribed with a general practitioner. Every kit should include detailed instructions for laypersons and a list of the age and weight of all participating children.

Other essential items for the travel medical kit include plasters, Steristrips, gauze swabs and bandages, elastic bandages, tape, Kurotex, second-Skin, Betadine (iodine), alcohol swabs, syringes for administering medication, needles for blister puncture, SAM splint, thermometer, insect repellent, sunscreen, oral rehydration solution and fine-tipped tweezers.

Although there are no studies on the treatment of altitude illnesses in children, the same management as for adults is recommended. The most important measure is descent, as long as the patient is still able to walk independently. Seriously ill children must be carried to minimise physical exertion. To facilitate descent for the child, analgesics (paracetamol, non-steroidal anti-inflammatory drugs such as diclofenac) or antiemetics (Itinerol or Motilium) may be helpful. All of these medications can be used without concern. However, they do not replace descent!

▪ **Table 42.1** Checklist: mountaineering first aid kit for children

Symptom	Medication
Pain	Paracetamol tablets, drops, suppositories; diclofenac tablets, drops, suppositories
Rhinitis	Nasal drops
Fever	Paracetamol or diclofenac
Cough	Possibly azithromycin tablets, drops, sachets, syrup
Sore throat	Lozenges
Diarrhoea	Oral rehydration, possibly azithromycin, possibly loperamide
Vomiting	Itinerol suppositories, domperidone tablets (sublingual)
Snow blindness	Close and cover eyes, black tea bags, diclofenac orally and as drops
Allergy	Cetirizine, in severe allergy dexamethasone
Urinary tract infection	Azithromycin tablets, syrup
Wounds	Tissue adhesive, possibly Fucidin gauze, possibly azithromycin tablets, syrup
Burns	Cooling, possibly Fucidin gauze, possibly azithromycin tablets, syrup
Sunburn	Possibly hydrocortisone foam
Nappy rash	Zinc phenol ointment, miconazole
Purulent conjunctivitis	Neomycin-polymyxin eye ointment
Altitude illnesses	Descent is essential!
AMS	Paracetamol, diclofenac, Itinerol suppositories, possibly acetazolamide

(continued)

Table 42.1 (continued)

Symptom	Medication
HAPE	Nifedipine, tadalafil
HACE	Dexamethasone

In severe AMS, oxygen, acetazolamide, dexamethasone or treatment in a portable hyperbaric chamber may be considered after consultation with a physician. Oxygen, nifedipine or tadalafil are indicated in the case of HAPE. These are only temporary measures; immediate descent remains the highest priority! Physicians can refer to the consensus recommendations for detailed information on dosing (Pollard et al. 2001), which must, of course, be adjusted to the child's body weight.

Any case of altitude illness in a child is one too much! Adherence to official guidelines for gradual ascent, avoidance of excessive physical exertion, and child-appropriate planning of the excursion are essential prerequisites.

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Infectious Diseases During Mountain Travel

Thomas Valentin

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In absolute terms, infectious diseases appear to play only a minor role in alpine and high-altitude medicine. However, the growing popularity of mountain tourism is steadily increasing the number of people susceptible to infections in these environments, thereby raising the significance of infectious diseases.

43.1 General Considerations

43.1.1 Risk Factors

In alpine and high-altitude medicine, infectious diseases encompass a broad spectrum and may, in some cases, result in life-threatening complications. The incidence of most infections decreases with increasing altitude. This is partly due to reduced nutrient availability for pathogens, lower temperatures and a decreased density of vectors and intermediate hosts. On the other hand, several factors in the alpine environment influence the development of infectious diseases and their complications (Basnyat and Starling 2015; Basnyat et al. 2001):

- Cold,
- Hypoxia,
- UV radiation,
- Low humidity,
- Increased risk of extreme weather events,
- Crowded sleeping conditions,
- Poor wastewater management,
- Reduced personal hygiene,
- Limited access to medical care.

Experimental evidence suggests that hypoxia impairs the immune system, with the defence against bacterial infections appearing to be particularly reduced, whereas antiviral immunity seems to be less affected (Basnyat and Starling 2015).

> Most infectious diseases become less common with increasing altitude.

43.1.2 Spectrum

In general, the spectrum of pathogens at altitude corresponds to that of the surrounding lowland areas. Thus, virtually all infectious diseases present in the locality are possible. These should be considered during travel preparation in terms of vaccinations, hygiene measures, exposure prophylaxis and, if necessary, malaria prophylaxis—even if the final destination is at altitudes where the pathogens are no longer present. The journey from the airport to the base camp also carries infection risks! It is advisable to seek pre-travel medical advice for relevant destinations.

> The spectrum of pathogens in the mountains reflects that of the surrounding region.

43.1.3 Vectors, Intermediate Hosts and Climate

Many infectious diseases are linked to the presence of intermediate hosts or vectors. Common vectors include mosquitoes, which may transmit plasmodia or arboviruses such as dengue virus and ticks (see ► Sect. 43.2.5). Intermediate hosts adapt to altitude, like other organisms. Highland populations, such as that of the pond snail (*Galba truncatula*), which serves as an intermediate host for the large liver fluke (*Fasciola hepatica*), live significantly longer than lowland populations and therefore represent better hosts (Vignoles et al. 2002). Due to predicted climatic changes, the distribution of certain vectors will change. It is also possible that previously harmless mosquitoes may acquire vector competence. In regions more severely affected by warming, an increasing number of people may seek refuge in the mountains to escape the uncomfortably high temperatures.

43.2 Infectious Diseases

43.2.1 Skin and Soft Tissue Infections

Various skin and soft tissue infections, such as wound infections, dermatophytoses, carbuncles, furuncles and pyoderma, as well as scabies or lice, may occur in mountaineers. Predisposing factors include poor hygiene, injuries, frostbite, moisture and sunburn. The combination of hypoxia and cold leads to delayed wound healing and increased susceptibility to infection (Sen 2009).

Wound infections can occur during climbing or mountaineering due to contaminated injuries, with the Gram-positive bacteria *Staphylococcus aureus* and *Streptococcus pyogenes* playing a predominant role (Forrester and Holstege 2010). These pathogens are transmissible from person to person, particularly in crowded accommodation (Decker et al. 1986). Hiking and mountaineering can lead to open sores and blistering of the feet, which may then become secondarily infected. Blisters on the feet are a very common problem. The risk of blister formation and infection clearly depends on the duration of the activity. Blistering was observed in 64% of participants in a cohort of hikers who were on the trail for more than 7 days (Boulware et al. 2003).

In a study conducted at two mountain huts (Hochschwab and Großglockner, Austria), serial swabs were taken from the feet and shoes of mountaineers, with 20% of those examined having pressure sores and blisters. At Großglockner, significantly more potentially pathogenic bacteria (*S. aureus*, *S. pyogenes*) were found than in the Hochschwab group. However, none of the individuals developed a skin or soft tissue infection during the study (Domej et al. 2010).

Patients with diabetes mellitus and especially diabetic neuropathy are particularly predisposed to mechanical ulcers and subsequent skin and soft tissue infections of the lower extremities; therefore, prophylactic measures such as appropriate footwear and regular inspection of the feet are essential.

The treatment of skin and soft tissue infections depends on their severity and extent. If empirical anti-infective treatment is required, *S. aureus* and *S. pyogenes* must be covered by suitable antibiotics. Prior to travel, tetanus immunisation status must also be checked.

> Hypoxia and cold promote skin and soft tissue infections.

43.2.2 Diarrhoeal Diseases

43.2.2.1 Relevance

Acute diarrhoeal illness during mountaineering expeditions can lead to life-threatening complications such as dehydration and electrolyte imbalances. Adequate rehydration is not always possible due to water scarcity and the time-consuming process of water treatment. It is possible that up to 10% of helicopter evacuations from the Himalayas could be attributed to complications of infectious diarrhoea (Pandey et al. 2001). As many as 30% of mountaineers en route to Everest Base Camp developed diarrhoea, and 26% required antibiotics (Wiseman et al. 2006). Among tourists in Nepal, diarrhoeal illness was the most common reason for seeking medical attention at 26.8%, while acute mountain sickness was the second most common at 15.6% of consultations (Hochedez et al. 2004).

Hikers reported diarrhoea in 56% of cases, with an average duration of 2 days, and in 12% of those affected, this resulted in a time loss of 3.6 ± 3.4 days (Boulware et al. 2003). Thus, diarrhoeal diseases represent one of the most important infectious problems during expeditions or trekking tours.

Diarrhoea at high altitude can lead to loss of time, but also to life-threatening dehydration.

43.2.2.2 Spectrum and Risk Factors

The causative pathogens do not differ from those found in the surrounding lowland regions and include bacteria (enterotoxigenic *Escherichia coli*, Salmonella, Shigella, *Campylobacter*), numerous viruses and protozoa (Giardia and amoebae), as well as parasites. Predisposing factors in alpine sports, but also during activities in lower regions, include contaminated food and water, reduced hand hygiene, high accommodation density and inadequate disposal of wastewater. Outbreaks of infectious diarrhoea therefore occur regularly during outdoor activities (Howie et al. 2003; Brugha et al. 1995). Noroviruses cause significant outbreaks due to their extreme infectivity, particularly during vomiting when a high viral load is released into the surrounding air (Kuo et al. 2009).

43.2.2.3 Treatment

The most important therapeutic measure is not antibiotic treatment, but oral rehydration. If this cannot be achieved, then descent remains the only option (A'Court et al. 1995). Nevertheless, when planning a tour, it is advisable to carry an antibiotic suitable for the treatment of acute bacterial diarrhoeal diseases (e.g. azithromycin). The additional use of loperamide may also be considered (Gundacker et al. 2017).

Oral rehydration is the most important measure in the management of diarrhoea.

43.2.2.4 Prophylaxis

Prophylactically, good drinking water hygiene is essential. The risk of acute diarrhoeal disease can be more than halved among hikers when appropriate measures are taken, whereas the risk is many times higher in individuals who regularly drink from streams or ponds (Boulware et al. 2003). Effective methods for water disinfection include boiling, filtration, chemical treatment and UV light, each with its own advantages and disadvantages (Albanus et al. 2021).

43.2.3 Respiratory Infections

43.2.3.1 Altitude

With increasing altitude, the hospitalisation rate due to respiratory syncytial virus (RSV) infection—as a surrogate parameter for infection severity in children—rises (Choudhuri et al. 2006). In developing countries, hypoxaemia in children with acute respiratory infection is associated with increased mortality and is observed more frequently at higher altitudes (Niermeyer 2009). Temperature decreases with increasing altitude, which in itself appears to influence the development and severity of respiratory infections (Mourtzoukou and Falagas 2007).

43.2.3.2 Physical Activity

Excessive training also predisposes to respiratory tract infections (Niemann 1995). Among elite athletes, respiratory infections are predominantly of viral origin, especially due to RSV, influenza and parainfluenza viruses, which are the same pathogens as in the general population (Spence et al. 2007; Cox et al. 2008). Very rarely, deaths due to bacterial superinfections and subsequent pneumonia following physical exertion and preceding respiratory infections have been reported (Duraković et al. 2009).

43.2.3.3 Hypoxia and Cold

Experimental data show that the combination of a preceding viral respiratory infection and hypoxia can lead to interstitial inflammation of the lung tissue. The combination of these two factors may predispose to hypoxia-associated pulmonary oedema (Carpenter et al. 1998). Furthermore, the decrease in temperature with increasing altitude, combined with lower humidity, leads to a reduction of pulmonary defence mechanisms (Basnyat and Starling 2015).

> Cold, hypoxia and physical exertion promote respiratory tract infections.

43.2.3.4 Pneumonia

Pneumonia occurs more frequently at high altitude, and the mortality rate from pneumonia increases with altitude (Khan et al. 2009; Pérez-Padilla and Franco-Marina 2004). The most important causative agent of bacterial pneumonia is *Streptococcus pneumoniae.*

The relatively rare intracellular pathogen *Legionella pneumophila* can be transmitted via water supply systems, particularly those that are infrequently used. Infection occurs through inhalation of contaminated aerosols released when showers or water taps are turned on. For this reason, measures to reduce this risk, such as hot water flushing or chemical treatment, should be implemented in mountain huts where necessary (Donegani et al. 2010).

43.2.3.5 Viral Respiratory Infections

Accommodating several people in confined spaces (as is often the case in huts or bivouacs) naturally increases the risk of acquiring respiratory viruses such as influenza, RSV, or SARS-CoV-2.

The COVID-19 pandemic also had unexpected effects on mountain rescue medicine, as additional protective measures for rescue teams had to be observed, and the organisation of training exercises was also made more difficult (Roy et al. 2021). It is possible that similar situations may recur.

43.2.3.6 Tuberculosis

Tuberculosis is, globally, a very common infectious disease and is caused by *Mycobacterium tuberculosis*. The incidence in Central Europe is relatively low, with higher rates in Eastern Europe. However, transmission has also been documented following a visit to a Bavarian ski hut (Gronauer et al. 2004).

As with many other infectious diseases, there is an association with altitude, but also with the environment. In Peru, it has been shown that the combination of a rural environment (as opposed to urban areas) and altitude has a protective effect for the local population (Saito et al. 2006). In contrast to bacterial pneumonia, tuberculosis as a cause of death decreases with increasing altitude (Pérez-Padilla and Franco-Marina 2004). This is probably related to the fact that the virulence and transmissibility of *M. tuberculosis* decrease with increasing hypoxia, UV radiation and dryness (Basnyat and Starling 2015). Historically, tuberculosis sanatoria were often located in mountainous areas.

43.2.3.7 Prophylaxis

To reduce the susceptibility to respiratory tract infections, very cold inspired air should be avoided. This can be achieved by covering the airways, for example, with a scarf. Vaccines are available for influenza, RSV, pneumococci and SARS-CoV-2 and should be administered according to current vaccination recommendations.

43.2.4 Infections of the Urogenital Tract and Sexually Transmitted Diseases

Urinary tract infections, urogenital fungal infections and sexually transmitted infections are common. The spectrum of pathogens responsible for sexually transmitted diseases and fungal infections is independent of altitude and includes *Neisseria gonorrhoeae,* chlamydia, trichomonads, candida, herpes viruses, hepatitis B and HIV. Predisposing factors include reduced personal hygiene, increased sexual activity and new sexual partners (Basnyat et al. 2001). Prophylaxis consists of avoiding these factors.

Urinary tract infections also show no altitude-dependent differences in the pathogen spectrum and are usually treated empirically with antibiotics in mountaineers. Adequate fluid intake is also essential. Premature descent due to a urinary tract infection is rarely necessary.

43.2.5 Zoonoses

43.2.5.1 Ticks as Vectors

Tick-borne infections occur particularly during hiking and camping. The type of infection depends on the specific geographic region. In Central Europe, numerous pathogens such as *Borrelia burgdorferi*, the TBE virus, *Anaplasma phagocytophilum*, *Coxiella burnetii*, *Francisella tularensis*, Babesia, *Rickettsia slovaca* and the Crimean-Congo haemorrhagic fever virus are transmitted by ticks, most commonly by the castor bean tick (*Ixodes ricinus*) (Stanek 2005).

Globally, more than 50 other pathogens are transmitted by ticks, for example, *Borrelia duttoni*, *Rickettsia rickettsii*, *Rickettsia conorii*, Kyasanur Forest Disease (KFD) virus and Colorado tick virus. Due to global warming, tick-associated infections are now becoming problematic even at higher altitudes (Gray et al. 2009). In Italy, ticks have been detected at elevations up to 2000 m (Rizzoli et al. 2002), and in the Czech Republic up to 1260 m, with both tick density and biting activity decreasing rapidly with altitude (Daniel et al. 2005). Similar findings have been reported in Switzerland, but surprisingly, tick density increased with altitude up to 1020 m, indicating that climate conditions are a factor in addition to altitude. However, the prevalence of Borrelia-infected ticks decreased markedly with elevation (Morán Cadenas et al. 2007; Burri et al. 2007). In Austria, specifically in Styria (at the Gaberl mountain pass), *Ixodes ricinus* has been found at elevations up to 1350 m (Stünzner et al. 2006). It is projected that due to climatic changes, the habitat of *I. ricinus* in Europe will increase by 3.8% and expand to higher altitudes between 2040 and 2060 (Semenza and Suk 2018).

In a North American study on the Appalachian Trail in Pennsylvania, with a maximum elevation of 2034 m, 24% of hikers who spent at least 1 week on the trail experienced tick bites, and 3% of these developed infectious diseases, mainly Lyme disease but also granulocytic anaplasmosis (Boulware et al. 2003). Ticks are also found in the Himalayas; during the 1999 Everest Marathon (starting at 5184 m, finishing at 3446 m), two participants required tick removal under local anaesthetic, although it was unclear at which altitude the ticks had been acquired (Buckler and O'Higgins 2000).

Borrelia Burgdorferi

Lyme borreliosis is the most common tick-borne disease in Europe, with erythema migrans as the typical initial manifestation. The highest altitudes at which *Borrelia burgdorferi* has been detected in Central Europe are 1260 m in the Czech Republic and 1350 m in Austria, where 6.4% of ticks were infected, with prevalence decreasing significantly at higher elevations (Danielová et al. 2010; Stünzner et al. 2006). Most manifestations of Lyme disease can successfully be treated with doxycycline.

Tick density and Borrelia prevalence decrease with increasing altitude.

Tick-Borne Encephalitis

The tick-borne encephalitis (TBE) virus is prevalent in many Central and Eastern European countries, as well as in Russia and the Baltic states. The maximum altitude at which TBE was acquired over a 30-year period showed an annual increase of an average of 5.4 (±1.7) metres (Zeman and Bene 2004). In the Czech Republic, the TBE virus has been detected in ticks at elevations up to 1140 m (Danielová et al. 2010). TBE infection can be largely prevented by appropriate vaccination; therefore, vaccination is recommended in endemic areas and for travellers into those areas.

43.2.5.2 Diseases Transmitted by Other Vectors

Malaria

Malaria is a parasitic infection caused by Plasmodia, which complete part of their life cycle in human erythrocytes and are transmitted by female Anopheles mosquitoes. These usually require calm, clean bodies of water for reproduction, but above 2000 m altitude and below 16 °C, transmission is virtually non-existent. With increasing altitude, parasitaemia among local populations in endemic areas decreases linearly (Akhwale et al. 2004; Achidi et al. 2008).

The variable clinical presentation of malaria can complicate diagnosis under expedition conditions. Initial symptoms typically include fever, chills, headache, myalgia, cough, and sometimes diarrhoea or vomiting. Differentiation from other infectious diseases is not possible without laboratory testing (Poespoprodjo et al. 2023). Complications of falciparum malaria include confusion, impaired consciousness, coma, renal failure, pulmonary oedema and shock due to microcirculatory disturbances in the affected organs. Tropical malaria may therefore be misinterpreted as a high-altitude-associated illness.

The bundle of malaria prophylaxis measures depends on several factors, such as the destination, duration of travel and availability of medical care at the location (Rothe et al. 2022). Pre-travel medical advice is strongly recommended for journeys to endemic areas.

> Malaria can be mistaken for altitude-related illnesses.

Schistosomiasis

This parasitic disease, with a long incubation period (2–7 weeks to the generalised stage, 4–12 weeks to the organ stage), is caused by schistosomes of the class Trematoda. These parasites undergo their initial cycle in freshwater snails and can infect humans through skin contact with contaminated water. Both the number of suitable water bodies and the snail population decrease with increasing altitude. Therefore, the risk of infection declines linearly with altitude (John et al. 2008; Ghebreyesus et al. 2002). The risk of acquiring this disease as a traveller is very low (Baaten et al. 2011).

Leishmaniasis

Infectious diseases caused by Leishmania include visceral leishmaniasis (kala-azar), cutaneous leishmaniasis (oriental sore), as well as mucocutaneous and cutaneous leishmaniasis in South America. For American forms of leishmaniasis, in addition to humid climate and dense forest, increasing altitude has also been described as a risk factor (Añez et al. 1994). In a study comparing the epidemiology of American cutaneous leishmaniasis in three different villages in Venezuela, it was shown that residents of the highest village (800 m) tested positive for Leishmania significantly more often than those in the two other villages (both below 300 m), with 800 versus fewer than 400 cases per 10,000 inhabitants over a 7-year study period (Jorquera et al. 1998). For tourists, leishmaniasis rarely poses a risk; it is primarily a disease of residents in endemic areas.

Hantaviruses

Hantaviruses are transmitted via excreta from rodents. At least 12 hantavirus species are pathogenic to humans. The clinical syndromes are haemorrhagic fever with renal syndrome (HFRS) and hantavirus cardiopulmonary syndrome (HCPS), the latter being associated with a high mortality rate of 30–50%. In Europe, the Puumala and Dobrava virus species are of particular importance, predominantly manifesting as HFRS and exhibiting significantly lower mortality rates (Dobrava virus 5–15%, Puumala virus <1%) (Avšič-Županc et al. 2015; Vial et al. 2023). Cleaning huts in spring poses a particular risk, as mice overwinter there and dried faeces can become aerosolised during sweeping, leading to infection. Staying in mountain huts has been described as a source of hantavirus infection (Zelena et al. 2011). Epidemic outbreaks of hantavirus infection occur repeatedly, often associated with increases in rodent populations following, for example, mild winters (Fabian et al. 2014). There is currently no established specific treatment.

Rabies

Rabies is a viral infection transmitted through animal bites or scratches, primarily by dogs but also by other mammals and by bats. Once the disease manifests, it is invariably fatal. During expeditions in remote regions, it is not always possible to avoid suspicious animals in difficult terrain. Therefore, rabies vaccination should be administered prior to travel to endemic areas. Prompt and appropriate wound care, as well as post-exposure immunoprophylaxis in the event of possible exposure, are essential (Hemachudha et al. 2013; Whitehouse et al. 2023; Plotkin 2000). In the event of an animal bite, the threshold for descent should be kept very low. During the Everest Marathon in 1999, a patient had to be evacuated by air following an animal bite; favourable weather conditions made this possible within 24 h (Buckler and O'Higgins 2000).

> In cases of suspected rabies exposure, immediate descent is required.

Other Zoonoses

Certain parasitic diseases such as *Echinococcus granulosus* and *multilocularis* are transmitted by mammals or their faeces (McManus et al. 2003). Contact with cats can result in infection with *Toxoplasma gondii*, *Bartonella henselae*, *Pasteurella multocida*, *Bordetella bronchiseptica*, Toxocara and Coxiella, as well as the diarrhoeal pathogens Campylobacter and Salmonella. Infections with *Chlamydia psittacii* from birds are rare and usually present as pneumonia. Dog bites, in addition to rabies, can lead to other severe infections, for example, due to *Capnocytophaga canimorsus*, *Pasteurella multocida* or *Staphylococcus aureus*.

43.3 Preparations

Thorough preparation for the regions to be visited and appropriate precautions (insect protection, repellents, travel medical kit, malaria prophylaxis, vaccinations) are important and should be organised well in advance. Travel medicine advice is recommended for relevant destinations at least 6–8 weeks before departure. Insurance cover should also be checked, for example, in case a helicopter evacuation becomes necessary. The following recommendations should generally be observed for the prevention and management of infections (modified after Basnyat et al. 2001):

- Immediate descent in the event of clinical deterioration or lack of response to any anti-infective agents administered,
- Regular hand hygiene,
- Use of clothing and repellents to prevent insect bites or stings,

- Use of treated or purified water,
- Avoid consumption of potentially contaminated or inadequately stored food,
- Protect the airways in cold conditions (e.g. with a scarf),
- Use sun protection,
- Maintain adequate hydration,
- Appropriate vaccinations and malaria prophylaxis according to destination,
- Check insurance cover for evacuation scenarios.

Conclusion

Most infectious diseases decrease with increasing altitude. Specific travel preparation should be tailored to the destination region, not just the final altitude. Adherence to hygiene measures is an effective means of protection against many infectious diseases. Some infections may be mistaken for altitude-associated illnesses due to their clinical presentation.

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44

Radiation Damage to the Skin in High-mountain Environments

Nina Frischhut and Josef Koller

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When the cold and darkness of long mountain nights come to an end, mountaineers appreciate the warming and invigorating effects of sunlight. However, as soon as the sun's UV radiation—intensified by altitude and reflection from snow and ice—reaches unprotected skin and eyes during the day, severe and, especially with prolonged exposure, potentially life-threatening consequences can occur.

44.1 Physical Aspects of UV Radiation

The three main action spectra of sunlight are

- long-wave infrared radiation,
- visible light and,
- ultraviolet (UV) radiation, so named because it is beyond the shortest visible wavelength—violet—in the solar spectrum.

Only about 10% of the sun's total energy is emitted as UV radiation. UV radiation consists of the long-wave UVA spectrum, with a wavelength of approximately 320–400 nm (depending on the source), and the shorter-wavelength UVB radiation with a wavelength of about 290–320 nm which has over a thousand times more energy. The UVA component of sunlight accounts for about 95%, while UVB makes up only 5%.

> UVB radiation has over 1000 times more energy than UVA radiation.

The even shorter-wavelength UVC radiation below 290 nm currently plays no significant role at the Earth's surface, as it is almost completely absorbed by the ozone layer in the stratosphere and therefore cannot reach the ground. The absence of the ozone layer (an ozone hole) would have dangerous consequences for all living organisms, including plants, as not only extremely energetic UVC radiation but also much higher levels of UVB radiation would reach the Earth's surface, potentially causing mutagenic damage in epidermal keratinocytes and melanocytes. The current ozone hole in the Antarctic region is the most significant. Mini ozone holes have also been described in Central Europe, but they do not currently appear to be expanding.

The penetration depth of UV radiation into the skin increases with wavelength, which in practice means that UVB radiation acts almost exclusively within the epidermis, while the longer-wavelength UVA radiation also penetrates into the deeper layers of the skin. There, in addition to its mutagenic effects, it can cause other types of damage, such as photodermatoses and degeneration of elastic fibres, resulting in premature skin ageing.

> UVB radiation penetrates only the epidermis, whereas UVA radiation also reaches the deeper layers of the skin.

During the winter months, the ratio of UVA to UVB radiation shifts towards UVA. The relatively greater effect of UVA radiation in winter compared to UVB is due to the lower filtering capacity of the atmosphere for UVA, which must travel a much longer path through the atmosphere in winter than in summer.

In practice, this means that UVA-induced skin diseases (photodermatoses, tumours, etc.) can also occur during the winter months, even though the total energy of both UVA and UVB radiation is significantly lower than in summer. In addition, UVA radiation is transmitted much more readily through glass (windows), as well as clouds and fog, than UVB.

> UVA radiation is only minimally filtered by glass, clouds or fog.

Fig. 44.1 Intense radiation exposure at high altitudes, further increased by reflection from snow and ice. (Image rights: J. Koller)

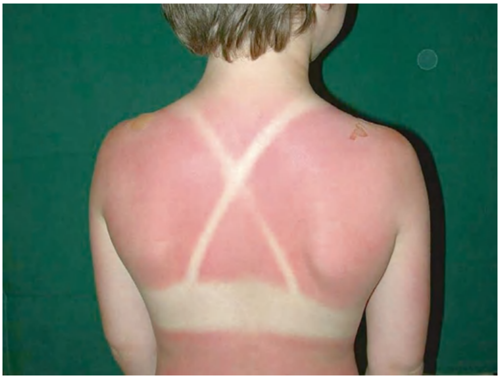


Fig. 44.2 Classic sunburn (solar erythema)

The intensity of UV radiation is significantly increased by altitude as well as by reflection from ice, snow and water (Fig. 44.1). Conversely, a cloudy sky, fog or shade reduces UVA radiation intensity by only about half, which means that UV protection is necessary even under such conditions.

44.2 Medical Aspects of UV Radiation

Both UVA and UVB radiation can rapidly cause skin damage, typically appearing within a few hours, as well as delayed damage that may only become apparent decades later.

44.2.1 Immediate Damage Due to Excessive UV Radiation

44.2.1.1 Sunburn (Solar Erythema)

The classic sunburn (*solar erythema*), which in some cases leads to blistering, occurs 3–6 hours after exposure as a result of UVB radiation exceeding the individual erythema threshold (Fig. 44.2).

Measurable DNA damage in epidermal cells occurs long before the individual erythema threshold is reached. The erythema reaches its maximum after 12–24 h. In the short-wavelength spectrum, UVA causes an immediate erythema following irradiation, which subsides after 48–72 h (Rhodes and Lim 2007).

The inflammatory solar erythema arises as a result of DNA repair processes, primarily in epidermal keratinocytes. In cases of extensive sunburn, proinflammatory cytokines (mainly interleukin-1 and TNF-α) are released, enter the circulation and cause systemic symptoms such as chills, fever and general malaise. Sunburn with UV-induced DNA alteration also forms the basis for the later malignant transformation of epidermal keratinocytes and melanocytes.

Sunburn, immunosuppression and photodermatoses are immediate effects of UV radiation.

Therapeutic management of solar erythema includes cooling and moisturizing compresses and lotions, as well as short-term use of moderately potent corticosteroid-containing topical preparations in light formulations, and anti-inflammatory agents such as aspirin, methylprednisolone or vitamin C. Blisters are not uncommon in extensive solar erythema and, if necessary (especially if painful), should be punctured under sterile conditions and dressed with antiseptic or disinfectant wound dressings, or silver-based dressings. Fluid and electrolyte replacement is necessary in cases of extensive solar erythema.

It is now known that not only UVB but also UVA radiation causes DNA damage, albeit to a lesser extent (Tewari et al. 2012). Repair of UV-damaged DNA is carried out by specific processes and enzymes, with the repair capacity of the skin declining significantly with age (Sauvaigo et al. 2019).

UVA radiation significantly increases melanoma risk, particularly during childhood and adolescence, representing a completely avoidable hazard from UV-emitting sunbeds (Cust et al. 2011).

In addition to the carcinogenic effects of UV radiation, immune cells in the epidermis and dermis are also damaged and functionally impaired by UV exposure. This is used therapeutically in phototherapy (PUVA) but also leads to transient, clinically relevant immunosuppression, which, for example, can promote the reactivation of herpes simplex viruses from the spinal ganglia following excessive UV exposure (Van der Molen 2001). The immunosuppressive effect of UV radiation is also implicated in the development of phototoxic and photoallergic reactions and, in part (in addition to direct DNA damage), in the development of malignant skin tumours.

44.2.1.2 Photodermatoses

In addition to photoallergic and phototoxic reactions caused by substances that are either applied directly to the skin or reach the skin via the bloodstream (e.g., medications—see ▣ Table 44.1), conditions such as lupus erythematosus, dermatomyositis and Darier's disease can also be triggered by UV light.

Among the most common photodermatoses is polymorphic light eruption (PLE), which presents with highly variable clinical features, sometimes resembling urticaria, eczema, erythema exsudativum multiforme, or a papulovesicular variant. The pathogenesis of this condition remains unclear. Clinical manifestation typically occurs when the patient is first exposed to sunlight in early summer. Characteristically, polymorphic light eruption improves over the course of the summer season as skin pigmentation increases. PLE is an indication for preventive narrowband UVB therapy (Lehmann and Schwarz 2011).

▣ **Table 44.1** Photosensitising Medications

Type	Active substance
Antiarrhythmics	Amiodarone
Antibiotics	Fluoroquinolones, nalidixic acid, tetracyclines, sulfonamides
Antifungals	Griseofulvin
Diuretics and antiarrhythmics	Thiazide, furosemide, amiodarone, quinidine
Nonsteroidal anti-inflammatory drugs (NSAIDs)	Naproxen, piroxicam, azapropazone
Calcium channel blockers	Nifedipine
Antipsychotics	Phenothiazines (chlorpromazine, thioridazine)
Retinoids	Isotretinoin, etretinate
BRAF inhibitors	Vemurafenib

44.2.2 Late Effects of UV Radiation on the Skin

44.2.2.1 Skin Tumours

There is no doubt that UV radiation is the most important causal factor in the development of skin cancer. 'Nonmelanoma' skin cancer, i.e., basal cell carcinoma (basalioma) and squamous cell carcinoma with its precursors Bowen's disease and actinic keratosis (see ◘ Fig. 44.3), arises primarily as a result of cumulative exposure to UV radiation over many years. In contrast, melanomas appear to be more closely associated with intermittent UV exposure (frequent sunburn). Here, too, the latency period extends over several decades.

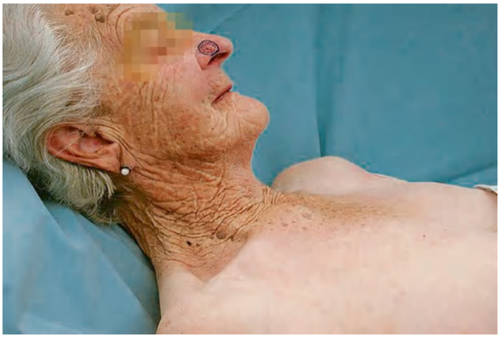
The carcinogenic effect of UV radiation occurs well below the erythema threshold. It can be assumed that any tanning of the skin is acquired at the cost of the carcinogenic effect.

44.2.2.2 Skin Ageing

Due to its physical properties, only long-wave UVA radiation is able to penetrate the dermis and cause damage to elastic fibres, leading to subsequent degeneration of these structural elements. The result is reduced skin elasticity and increased wrinkle formation.

In addition to genetic predisposition and smoking, UVA radiation plays a central role in premature skin ageing—a fact of which every tanning salon user should be aware (Uitto et al. 1998). Although skin ageing occurs prematurely, it still has a latency period of often several decades.

❯ Skin cancer and premature skin ageing are late effects with a latency period of several decades.



◘ **Fig. 44.3** Chronically sun-damaged skin and basal cell carcinoma on the nose

44.3 UV Protection

Protection against UV radiation must cover not only the UVB range but also the UVA range. UVA radiation is considered the main trigger of photodermatoses such as polymorphic light eruption and photoallergy and also causes premature skin ageing. However, there is clear evidence of a causally significant role of UVA radiation in the development of melanoma.

Previously, it was believed that prophylactic UVA exposure in tanning salons could significantly reduce the carcinogenic effect of UVB radiation due to UVA-induced skin pigmentation. However, it is now known that UVA radiation, in addition to its direct carcinogenic potential for melanocytes, does not protect against the development of non-melanoma skin cancer (squamous cell carcinoma and basal cell carcinoma/basal cell epithelioma). This is because UVA-induced tanning results from pigmentation of the deeper epidermal layers, leaving the overlying keratinocytes and melanocytes completely unprotected and exposed to carcinogenic UV radiation (Miyamura et al. 2011).

❯ Tanning from sunbeds does not protect against skin cancer.

Another preventive measure against UV radiation, the oral intake of an extract from the fern *Polypodium leucotomos*, has not become widely established due to its rather limited protective effect (protection factor 2–3). However, the photoprotective, antioxidant and anti-inflammatory effects of this fern have been shown to reduce the frequency of polymorphic light eruption in individuals affected by this recurrent dermatosis (Rodríguez-Luna et al. 2023).

Nevertheless, the three most important pillars of UV protection remain exposure avoidance, protective clothing and the application of sunscreens. The most reliable and safest method is exposure avoidance—that is, avoiding sun exposure, especially during peak intensity between 11:00 a.m. and 3:00 p.m., ideally by staying indoors.

It should not be forgotten that staying in the shade of a parasol offers only limited protection (equivalent to a sun protection factor of about 2) due to the effect of scattered radiation.

44.3.1 Textile UV Protection

Textiles provide highly variable UV filtering depending on the type of fibre used, their colour, weaving technique and other factors. Specialised retailers now offer textiles labelled with their sun protection factor (SPF).

44.3.2 Sunscreens

Commercially available UV filter substances consist of chemical and/or physical UV filters. Chemical filters absorb incoming UV radiation and convert most of it into heat energy, which is generally not perceptible on the skin. Some chemical filter substances undergo molecular changes as a result of UV radiation. This 'photoinstability' can, under certain circumstances, lead to a significant loss of efficacy. However, this loss of efficacy does not occur with some UV filter substances such as Mexoryl SX and Tinosorb (Wolf 2009).

Approximately 30 UV filter substances are currently approved in EU countries, most of which are effective only within a specific part of the UV spectrum. For this reason, most sunscreens contain combinations of several UV filter substances to cover the entire UV spectrum.

Physical filters are mineral pigments such as titanium, zinc or iron oxide, which primarily reflect UV radiation but can also to some extent absorb it. The advantage of physical filters is in their low absorption rate and low allergenic potential. Modern production techniques can reduce titanium or zinc oxide to particle sizes of 1–100 nm (microparticles), thereby avoiding the undesirable 'whitening effect' of macropigment particles. Ultrafine titanium oxide primarily provides protection in the UVB range, while ultrafine zinc oxide mainly protects in the UVA range. However, in this form, neither substance provides filtering for visible light or infrared radiation.

Because of their limited action spectrum and, in the case of macropigment particles, relatively low sun protection efficacy, physical filters are often combined with chemical filters. Titanium dioxide can be formulated as a micropigment particle suspension through special manufacturing processes, so that when used as a single substance, it can achieve a sun protection factor of about 15 without producing a whitening effect on the skin. This suspension is particularly recommended for children owing to its ease of application and lack of known toxicity (Wolf 2009).

Chemical filter substances can now be incorporated into liposomal bases making it possible to achieve significantly improved water and sweat resistance. Nevertheless, drying off after swimming or wiping away sweat can still remove a large proportion of the protective effect, even with these substances.

44.3.3 Sun Protection Factor

The sun protection factor (SPF) of a sunscreen in the UVB range indicates how many times longer the skin can be exposed to sunlight after applying the sunscreen before redness (erythema) occurs. In the EU, the SPF is determined using a standardised procedure for UVB with a fixed sunscreen concentration on the skin of 2 mg/cm^2.

The UVA protection factor is determined in a much more complex manner using several methods, primarily because the erythema threshold cannot be used due to the lack of erythemogenic effect of the longer-wavelength UVA spectrum. According to a recommendation by the European Commission, a commercially available UVA sunscreen within the EU should provide at least one-third of the UVB protection factor's efficacy in the UVA range (Wolf 2009).

UVA protection should amount to one-third of the stated UVB protection.

44.3.4 Risks Associated with the Use of Sunscreens

In principle, sunscreens are considered safe for humans when used in the recommended quantity, although the ingredient oxybenzone has been a concern due to its endocrine activity at high doses in animal studies.

When used correctly and regularly, sunscreens reduce the risk of squamous cell carcinoma and its precursors (Darlington et al. 2003), as well as the development of melanoma (Autier 2005). Many photodermatoses and premature skin ageing caused by UV radiation can also be prevented or at least reduced through the use of sunscreens.

The two main problems in the practical use of sunscreens are, first, that the reduction of the critical threshold for sunburn (minimal erythema dose) achieved by these substances does not correlate with a reduction in carcinogenic risk. It is known that a carcinogenic effect occurs at approximately 50% of the erythema-inducing dose.

❯ UV radiation is carcinogenic even well below the sunburn threshold.

In practice, this means that even after applying sunscreen, a carcinogenic effect of UV radiation can occur long before visible sunburn develops, giving users a false sense of security.

The second problem concerns the almost universally observed under-application of sunscreen, resulting from applying too thin a layer to the skin. According to EU standards, the efficacy and filter performance of sunscreens are determined at an application rate of 2 mg/cm^2. However, in everyday use, the typical amount applied is only about half of this—approximately 1 mg/cm^2. One might assume that this would halve the sunscreen's efficacy. Unfortunately, this is not the case. In fact, the UV filter efficacy of sunscreen applied in this way corresponds to only the square root of the stated protection factor.

This means that if only half the standardised amount is applied per unit area, a sunscreen with a protection factor of 20 does not provide a protection factor of 10, but the square root of 20—that is, only about 4.3 (Faurschou and Wulf 2007).

❯ Applying too little sunscreen reduces its efficacy disproportionately.

Considering that the carcinogenic effect of UV radiation occurs long before visible erythema develops, it becomes clear that if sunscreen is under-applied—especially under the challenging conditions regularly faced by mountaineers—adequate protection cannot be expected.

Conclusion

The intensity of UV radiation in mountainous regions is significantly increased by altitude and by reflection from ice and snow. UVA radiation can induce skin cancer, cause premature skin ageing and is a major factor in the action spectrum of many photodermatoses. Relative UVA intensity is increased during the winter months, behind glass and under cloudy conditions. Therefore, UV protection must cover the entire UV spectrum.

> In photoprotection, exposure avoidance and textile protection are just as important as sunscreens. The protective effect of sunscreens is primarily based on the prevention of sunburn, but protection against skin cancer does not necessarily correlate with protection against sunburn. Sunscreens are usually applied too sparingly, leading to a disproportionately reduced level of protection.

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Ocular Damage at High Altitude

Gerhard Schuhmann and Barbara Teuchner

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What applies to expeditions in high mountain regions is similarly true in other inhospitable areas of the world. Environments characterised by remoteness, distant from civilisation, extreme climate, unique environments (deserts, rainforests, ice and snow, caves), objective hazards, poor hygiene, specific diseases and unfamiliar dietary conditions can be challenging for the eye. Typically, these individual factors occur in varying combinations. Subjective effects on the visual system are usually perceived as non-specific discomfort, pain, and functional impairment. The intensity of symptoms does not directly correlate with the degree of damage. Therefore, any ocular symptom should be regarded as a warning and an indication of an anomaly and should be taken seriously.

Pathologies, regardless of their origin (exogenous or endogenous), can in principle affect all parts of the eye (eyelids, conjunctiva, cornea, sclera, choroid, lens, vitreous body, retina, optic nerve) to varying degrees. Anomalies that directly impair vision are generally perceived as more striking and are therefore more likely to be noticed. In this situation, the brain structures involved in information transmission and processing must also be considered.

If the visual system is modelled on an analogue camera, the image is projected onto the retina, as onto photographic film, by the cornea and lens, and the visual signals are transmitted via the optic nerve and the cerebral visual pathway to the visual cortex, where they are interpreted and, in conjunction with other brain regions, integrated into our perception of the world. Responses to the received information are then initiated in higher brain centres, resulting in purposeful actions.

It is evident that disruptive influences on the complex system of visual perception can affect not only the visual components (visual acuity, visual field, colour vision, contrast sensitivity, spatial perception, motion perception, twilight vision) but also cognitive functions. The latter may lead to a multitude of symptoms ranging from reaction capacity to decision-making.

The following article aims to outline the effects of high altitude and other environmental noxious factors (physical, chemical, microbiological) on the healthy eye and on eyes with pre-existing pathological or surgically induced changes and to consider practical therapeutic and strategic consequences.

45.1 Effects of High Altitude on the Normal Visual System

45.1.1 General Effects

The eye, like any other organ, is influenced by the conditions prevailing at high altitude, with low atmospheric pressure and the associated reduced partial pressure of oxygen being of primary importance. As detailed elsewhere in this book (▶ Chap. 3 ff.), atmospheric pressure does not decrease linearly with altitude. Assuming a pressure of 100 kPa at sea level, it drops to 50 kPa at an altitude of 5000 m and falls to 33–34 kPa at the summit of Mount Everest (8800 m). The associated reduction in the oxygen-carrying capacity of haemoglobin (to 70% at 5000 m, and only 30% at 8800 m of sea-level values) explains, through hypoxia, the demonstrable structural and functional changes.

The high-altitude changes in all visual (ocular and cerebral) can be detected functionally—and often morphologically—if sufficiently sensitive methods are deployed. Anatomically, corneal thickening (due to impaired endothelial function), an increase in macular thickness (Fischer et al. 2012), and oedema of the optic disc and optic nerve without significant symptoms have been observed. It is likely that with further refined techniques (magnetic resonance imaging, positron emission tomography [PET], optical coherence tomography

[OCT]), even subtler structural changes will become detectable.

Due to its autoregulation, the functional capacity of the eye is highly resistant to harmful influences, so that noticeable impairments occur only very late. Although hypoxia caused by rapid pressure drop (hypobaric hypoxia) leads to stepwise disturbances of individual visual sub-functions, these are of little significance in the reality of high-altitude mountaineering due to the slowness of pressure decrease and the limited relevance of these subfunctions to the high-altitude environment: According to NASA findings, up to about 4000 m, dark adaptation and colour vision are affected; between 4000 and 5000 m, intraocular pressure increases; from 5000 to 6000 m, disturbances of accommodation, convergence, visual field and distance estimation occur. At altitudes above 6000 m, without acclimatisation or supplemental oxygen, further reductions of visual acuity occur (NASA, cited in Hinghofer-Szalkay 2013).

The central visual acuity of a middle-aged adult can be assumed to be 0.8–1.2 (clinically referred to as 100%) if the other sub-functions also remain within the normal range. Considering that the legal requirement for safe participation in road traffic as a car driver is a minimum visual acuity of 0.5 (‘50%’), it becomes clear what enormous functional reserves exist for adequate functioning of the entire visual system even under extreme conditions at high altitude. The fact that even blind mountaineers, with appropriate support measures, can undertake high-altitude climbing lends weight to this consideration.

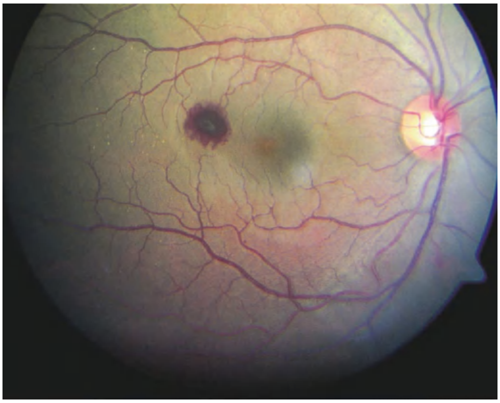
Nevertheless, adherence to all recognised guidelines and recommendations of altitude medicine—such as physical fitness, acclimatisation, UV and cold protection and maintenance of fluid balance—is, of course, essential and indispensable for the healthy achievement of personal high-altitude goals.

45.1.2 High-altitude Retinopathy

High-altitude retinopathy (HARH), first described by Singh et al. in 1969, has since been the subject of numerous studies employing various methodologies and involving large case numbers. Retinopathy reflects the response of retinal vessels to the decreasing partial pressure of oxygen in inspired air. The resulting breakdown of the blood-retina barrier leads to characteristic streak-like retinal haemorrhages, which are often accompanied by oedema of the optic disc and optic nerve.

The main factors influencing the onset and severity of HAR are the rate of ascent (duration of acclimatisation), degree of physical exertion and the altitude reached. From an altitude of around 5000 m, there is a high probability of retinal haemorrhages occurring, and above approximately 7000 m, more than 90% of all high-altitude mountaineers, regardless of gender, are affected (◘ Figs. 45.1 and 45.2).

As the eye is the only organ that allows direct observation of blood vessels, the condition of the retinal vessels provides immediate insight into the status of the cerebral vessels. Accordingly, the presence of HARH should be taken as an indication of altitude sickness, high-altitude pulmo-



◘ **Fig. 45.1** Retinal haemorrhages after an ascent of Mount Everest, asymptomatic

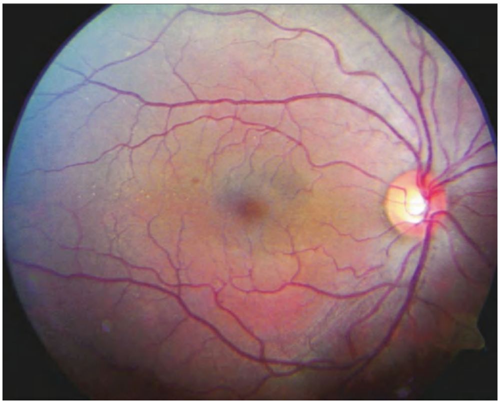


Fig. 45.2 Fundus after 2 months, no significant residual findings

nary oedema, and high-altitude cerebral oedema, even though the correlations in this regard are not yet sufficiently established (Barthelmes et al. 2011; Wiedmann and Tabin 1999). In such cases, confirmation using an Acute Mountain Sickness (AMS) score is required.

Subjectively, haemorrhages are rarely clearly perceived, as they usually affect only peripheral areas of the visual field. Only haemorrhages in the macular region are immediately noticed and, due to the significant loss of visual acuity, represent a striking event. Various groups of authors have proposed classifications of the severity of HARH, based on visual acuity, the extent of haemorrhages and macular findings (Wiedmann and Tabin 1999; Mader and Tabin 2003; Morris et al. 2007; Barthelmes et al. 2011).

The resulting recommendations, although not uniform, are consistent in the view that, in the presence of HARH, further ascent or continued stay at high altitude is not advisable (relative contraindication). If the macula is involved or if there are additional symptoms of altitude illness, active or passive descent from the respective altitude should be sought as soon as possible.

45.2 Effects of High Altitude in Pre-existing Conditions

The following considerations address some of the most common pathological conditions of the visual system, which, if poorly managed, can lead to serious problems during stays at high altitude. On the other hand, it can be justifiably stated that, with good preparation, there are almost no restrictions on mountaineering from an ophthalmological perspective. In cases of doubt, the treating ophthalmologist or an ophthalmologist experienced in altitude medicine should be consulted.

45.2.1 Monocular Vision

The loss of one eye or a state of functional monocular vision is generally compensated for by adaptation within a few months. All functions of the healthy eye are more than sufficient to meet the demands of high-altitude environments, and there are no specific tasks that require two eyes. In a particular form of functional monocular vision, amblyopia of one eye, central visual acuity is lacking, but the entire peripheral visual field remains intact and thus supplements the binocular visual field.

The main concern in monocular vision must be to avoid acute impairment of the healthy eye, which in the high mountains could pose an extreme risk to the individual and their companions. This fact must be clear to all members of a group, and every effort should be made to prevent injury. The most important preventive measure is the use of suitable protective eyewear to prevent injuries from metal, ice or rock fragments, as well as from the shafts of ice axes and climbing equipment. The best choice is sunglasses with hard polycarbonate lenses with high impact resistance.

45.2.2 Glaucoma

Glaucoma refers to a group of eye diseases that lead to loss of optic nerve fibres and, over time, typically cause visual field defects and loss of visual acuity. The most common form is associated with increased intraocular pressure, which is amenable to treatment. Well-controlled glaucoma with adequate visual function and a good visual field generally does not pose a barrier to activities at high altitude. Spontaneous significant increases in intraocular pressure, leading to further optic nerve fibre damage, are not expected during temporary stays at high altitude. Only in advanced cases, where progression is already anticipated under normal conditions, might hypoxic conditions accelerate visual field loss.

Currently, three main groups of pressure-lowering agents are prescribed: β-blockers (timolol maleate, etc.), prostaglandins (latanoprost, etc.) and alpha-2 adrenergic agonists (brimonidine tartrate, etc.). When using β-blockers, it should be noted that they can also lower blood pressure and heart rate and may trigger asthma attacks. This can hinder or prevent altitude acclimatisation, so in such cases, prostaglandins should be considered instead. Another alternative is the use of oral acetazolamide (Diamox R), which may also have beneficial effects on acclimatisation.

45.2.3 Diabetes

Patients with well-controlled diabetes and no evident changes in the retinal vascular architecture (fluorescein angiography) are probably not at greater risk at high altitude than the general population. However, in the presence of diabetic retinopathy, additional hypoxia is likely to exacerbate vascular damage, and the risk of developing altitude-related retinal haemorrhages (HARH) is also significantly increased.

Before deciding to travel to high altitudes, a thorough ophthalmological examination—if necessary, including laser treatment—accompanied by appropriate risk counselling, is strongly recommended.

45.2.4 Vasculopathies

Retinal vascular diseases pose an increased risk for stays at high altitudes. Patients with occlusions of the central retinal artery or with occlusions of the central vein or its branches in one eye are always at risk of experiencing the same event in the other eye. Under the influence of factors present at high altitude, this risk is certainly significantly increased. An elevation in haematocrit—associated with dehydration—also increases the likelihood of further retinal vascular occlusions.

45.2.5 Retinal Detachment

The pathogenesis of retinal detachment does not entail an increased risk during activities at high altitude. Retinal detachments that have been surgically repaired also do not carry a higher risk of recurrence at higher altitudes. Patients with recently operated retinal detachments with intraocular gas tamponade should avoid travel to moderate or high altitudes until the gas bubble has been fully resorbed, as expansion of the gas may cause severe complications. This also applies to air travel. For patients treated with silicone oil tamponade, this does not cause problems under altitude conditions; at most, visual impairment may be a limiting factor.

45.2.6 Age-Related Macular Degeneration

Age-related macular degeneration (ARMD), in both its dry and wet forms, leads to dysfunction of the central retinal cells and thus to loss of central visual acuity, while the peripheral retina and thus the visual field remain unaffected. There is no evidence that high-altitude conditions influence the progression of ARMD, but in individual cases, the visual acuity of both eyes will likely form the basis for decision-making.

45.2.7 Cerebral Factors

All diseases affecting the central nervous system can also damage the visual pathway, the visual cortex, and higher-order centres of information processing. Under hypoxic conditions, such lesions may become more pronounced and lead to serious risks.

45.2.8 Refractive Surgery

The appealing idea of pursuing a passion for the world's mountains without glasses or contact lenses has, in recent years, led to a considerable increase in interest in surgical correction of refractive errors (myopia, astigmatism and hyperopia). Several proven and recognised methods are now available for this purpose; the once negatively regarded radial keratotomy, well known in mountaineering literature, has long since been abandoned (Krakauer 1997; Kohnen 2012).

One group of treatments uses an excimer laser to reshape the corneal contour, thereby altering its refractive power and permanently correcting the refractive error, comparable to a contact lens that, instead of being placed on the cornea, is sculpted into it.

In a second group, artificial lenses are implanted into the eye in addition to the natural lens (comparable to a contact lens inside the eye), either in front of or behind the iris. The third option involves the removal of the natural lens and its replacement with an artificial lens, the power of which compensates for the previously required spectacles.

All established methods have their advantages and disadvantages, but are scientifically validated and recognised. No recommendation can be made as to which method is better suited for high-altitude mountaineering based on current experience. The choice of method must be made individually, considering age, the degree of refractive error to be corrected and other factors. Our own experience with excimer correction and lens implantation suggests that either technique is equally appropriate for travellers to high altitudes.

In recent years, the literature has focussed primarily on the laser-based methods LASIK, LASEK, PRK and epi-LASIK. Occasional reports of fluctuations in visual acuity have been described; these are of little practical relevance, as the subjective loss of 1–3 lines of visual acuity is not generally perceived as significant. It can therefore be concluded that the refractive surgical methods currently in use, in contrast to those now rightly considered obsolete, are very well suited for high-altitude activities.

45.3 General Risk Factors in Extreme Environments

45.3.1 UV Light

The term ultraviolet radiation refers to wavelengths in the range of 180 to 400 nm, with UVA (315–400 nm) and UVB (280–315 nm) being the strongest and thus the most significant component of UV light, while UVC (180–280 nm) are almost entirely or completely absorbed by the atmosphere. The proportion of UV light increases by approximately 15% for every 1000 m of altitude gained and is further intensified by reflection from water (twofold), snow and ice (eightfold) and fog. All ocular structures, from the eyelids through the conjunctiva and cornea to the lens and retina, can be affected by UV radiation.

Symptoms typically occur 4–8 h after unprotected exposure and are collectively referred to as ‘snow blindness’. The eyelids are swollen, the conjunctiva is reddened, and blepharospasm (spasms of the eyelids) frequently occurs. The corneal surface shows minute defects, sometimes erosions, and may also be oedematous. The erosions cause a foreign body sensation, pain, photophobia and tearing.

Snow blindness is generally harmless and heals spontaneously within a few days without treatment, but in extreme environments, the associated pain and visual impairment can lead to significant hazards.

Treatment consists of pain relief with oral analgesics, local application of cold and an eye bandage/patch with antibiotic eye ointment and vitamin A eye ointment, or artificial tears. Topical anaesthetic eye drops can be used in emergencies; they provide immediate pain relief but should only be applied for a short period.

■ UV Protection with Protective Eyewear

When staying at high altitudes, it is essential to protect the eyes from UV exposure with appropriate protective eyewear. Glacier, snow and sports goggles must be designed to prevent radiation from entering from the sides (stray light) and to provide complete UV protection (UV-400 filter). The relevant regulations are set out in the European Standard EN 1863:1997.

Ideally, lenses of category 4 with 3–8% light transmission (92–97% filtering out of visible light) and a grey tint should be used, as these allow minimal colour distortion. Standard spectacle lenses have a light transmission of 80–100%; conventional sunglasses transmit 18–43% of light. Polarising coatings and anti-reflective treatments can further improve visual comfort by reducing disturbing reflections. The use of peaked caps or wide-brimmed hats with a dark underside can also reduce exposure to radiation to a comfortable level in suitable situations.

It is particularly important to emphasise the need to carry spare glasses of the same quality. If no replacement is available in the event of loss, an emergency solution such as a loosely woven cloth, a strip of cardboard with slits for vision or an optical lens covered with perforated paper or cardboard can help prevent the worst outcomes.

45.3.2 Inflammations of the Eye

Although the incidence of bacterial or viral conjunctivitis (red eye) is unlikely to be increased at high altitude, the often-inadequate hygiene conditions in these regions mean that occasional cases occur. These can be rather troublesome, though generally they are harmless.

The travel medical kit should include a suitable selection of antibiotic eye drops, which can be usefully supplemented with non-steroidal anti-inflammatory drugs and, for short-term use, steroid-containing eye drops.

The use of Beta-Isodona (povidone-iodine) in a self-prepared dilution with H_2O or physiological saline at approximately 1:30 has proven to be an effective broad-spectrum antiseptic with activity against bacteria, viruses, fungi, spores, and protozoa. It is an effective and inexpensive alternative, as it is available in all countries and can be used for acute care of the local population without depleting the expedition’s medical supplies.

45.3.3 Eye Injuries

Although the eye accounts for only a small proportion of the body surface area, all activities in extreme environments carry the potential for ocular injury due to the specific risk factors and the nature of the tasks performed. Most injuries are minor, but they can cause serious problems in carrying out specific tasks such as mountain climbing. Timely recognition and treatment are therefore essential for the success of the undertaking, both for the individual and the group.

45.3.3.1 Erosions

Corneal erosions are epithelial defects caused by mechanical trauma (for example, handling objects, contact lenses, UV light), which can be very painful. Diagnosis in the field is based on history and pain symptoms. With lateral focal illumination and a good torch, a sharply demarcated dull area can be seen on the otherwise shiny cornea (which can be stained with sodium fluorescein). Therapeutically, the eye is immobilised with an antibiotic eye ointment bandage/patch until healing occurs.

45.3.3.2 Foreign Bodies

Foreign bodies may be blown into the eye by the wind (sand, ice particles, insects) or may splinter off during work with rock, ice or mountaineering equipment and strike the eye. Diagnosis is again based on history and inspection of the eye with lateral focal illumination. Foreign bodies are usually visible as dark spots in the conjunctiva or cornea and can be removed with moistened cotton swabs or can be removed easily using the corner of a handkerchief. If no foreign body is visible, the inner surface of the upper eyelid must be inspected after eversion (turning inside out—practise this at home beforehand).

45.3.3.3 Penetration/Perforation

Foreign bodies that reach the eye with high energy are usually splinters from metal tools (ice axe, climbing hammer) and can penetrate or perforate the eye. These whether with or without a foreign body remaining in the eye, must be referred to an ophthalmic clinic as quickly as possible. For transport, the eye should be slightly covered with a sterile patch and, if possible, systemic antibiotic therapy should be initiated.

45.3.3.4 Contusion

Contusions are eye injuries caused by blunt objects or falls and always raise suspicion of involvement of deeper ocular structures. Prompt transfer to a specialist clinic is therefore required.

45.3.4 Contact Lenses

The use of contact lenses is undoubtedly an excellent alternative to spectacles for many mountaineers. Limiting factors for their use include hypoxia, hygiene issues, difficulties handling lenses in cold and windy conditions, dehydration and UV radiation.

For many reasons, the use of soft daily lenses is recommended, as they place the least metabolic burden on the cornea at hypoxic altitudes and thus minimise the risk of the dreaded keratitis with ulcer formation. As inserting contact lenses becomes difficult in the cold and under physical strain, assistance from companions should be considered.

The contact lens supply should be carried on the body, and insertion should be performed quickly, as the lens becomes stiff very rapidly in the cold. It may be acceptable, under certain circumstances, to leave the lenses in the eye for an extended period on summit day, provided there are no symptoms of irritation.

Should keratitis occur despite all precautions, the patient must be evacuated to a lower altitude and to a clinic after initiation of local and systemic antibiotic therapy.

45.3.5 Dry Eye

Although dry eye syndrome has in recent years become a widespread phenomenon of civilisation, with varying degrees of clinical significance (air conditioning, central heating, air pollution, etc.), it can undoubtedly also present as an unpleasant problem during outdoor activities and in extreme climatic and high-altitude environments.

Symptoms range from mild irritation to severe impairment due to drying of the corneal surface (small erosions), with frequent reports of foreign body sensation, burning, itching, stabbing pain, and a feeling of pressure behind and beside the eye radiating to other parts of the skull. The irritation, caused by the loss of tear film quality and resulting in an unprotected ocular surface, leads intermittently to reactive tearing, which, however, cannot provide lasting relief due to the lack of mucous and lipid components.

Wind and hypoxia, amongst other factors, can significantly worsen symptoms in individuals with tear film deficiency syndrome at high altitude. In such cases, increased tear supplementation is necessary, even if annoyingly inconvenient. Protective eyewear can provide additional support, and consideration should be given to the temporary or permanent closure of the lacrimal puncta prior to the expedition.

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Anxiety and Stress in Alpine Sports

Frans van der Kallen

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Mountain activities naturally place demands on the participant. This applies equally to the physical, mental, emotional, and social dimensions of the individual's current state. In order to respond appropriately to such demands, mechanisms were developed early in evolution that can collectively be described as the neuroendocrine stress response. Anxiety as an emotion often, but not necessarily, occurs in the context of this response. A strict distinction between the terms 'anxiety' and 'stress' is difficult from this perspective. The terms can at least partially be used synonymously. However, the phenomena of anxiety and stress not only represent the possibility of adaptation to adverse environmental conditions, but also enable the experience of 'pleasure' in overcoming challenging situations.

46.1 Anxiety and the Neuroendocrine Stress Response

The neuroendocrine stress response is of great importance for the survival of individuals in dangerous situations. It played a decisive role in evolution (Hüther 1997). Stress, among other things, regulates particularly intense and lasting neuronal restructuring in terms of the plasticity of the brain, both in constructive and destructive senses, depending on how stress is subjectively processed, how intense it is, and how long it lasts. Stress has direct and indirect effects on all aspects of thinking, feeling, and behaviour. The neuroendocrine stress response is therefore also the 'great modeller' of the brain (Hüther 1997).

46.1.1 Milestones in Stress Research

Initial physiological and biochemical research into stress mechanisms was later complemented by psychological models of stress processing and coping. In particular, the idea of 'positive' and 'negative' stress (Selye 1946, 1956, 1975) as well as the significance of 'cognitive appraisal' (Lazarus and Folkman 1984) of a stressor remain valid to this day.

Coping with stress and anxiety is a dynamic process that is significantly influenced by internal attitudes and experiences. On a neuroanatomical and functional level, the central anxiety and stress system can be described in detail (e.g. Lahousen and Kapfhammer 2018). In addition to direct effects on autonomic control centres, there are close connections to attention, reward and motivation systems, as well as to the hippocampus as the centre of memory formation (Esch 2012). Stress affects not only most regions of the brain, but also the entire body, such as influencing immune defence (Dhabhar 2014; Breeze et al. 2024) and fertility (Ilacqua et al. 2018; Palomba et al. 2018).

Key milestones in stress research are summarised in ▪ Table 46.1.

46.1.2 Symptomatology of Anxiety and Stress

Since the psychological or emotional component (anxiety) cannot be clearly distinguished from the physical or physiological component (stress), a separation into two groups of symptoms is not made. Similarly,

▪ **Table 46.1** Stress research in the twentieth century

Topic	**Author/ year**
Description of the physiological effects of strong emotional stimuli; the role of catecholamines in mediating the stress response; fight or flight as a response	Cannon (2015)
Stress as a non-specific response to demands	Selye (1946)
Differences in the stress response of individuals depending on the stressor	Mason (1971)
Distinction between ‘distress’ and ‘eustress’	Selye (1975)
Subjective appraisal of a stress-inducing situation as a key process in coping	Lazarus and Folkman (1984)
‘Allostatic load’ as the ‘cost’ of chronic stress: significance in the development of mental and cardiovascular disorders	McEwen (2007)

a systematic allocation to different levels (e.g. cognitive–emotional–autonomic) would only be possible with considerable imprecision. It is striking that most anxiety symptoms can be described on a physical level, which underlines the fundamental evolutionary significance of anxiety and stress as preparation for survival-promoting behaviours (fight, flight, play-dead).

The following list provides an overview of the most common symptoms.

Symptoms of Acute Anxiety or Acute Stress

- Tightness, oppression, inner restlessness
- Fear, fright, ‘anxiety’ as the primary emotion
- Increased (or decreased) heart rate
- Elevated (or decreased) blood pressure
- Chest pressure, palpitations
- Altered (usually increased) respiratory rate, shallow breathing, shortness of breath, sensation of suffocation
- Dry mouth, difficulty swallowing, globus sensation
- Epigastric complaints: discomfort, belching, nausea, vomiting
- Abdominal complaints: bloating, diarrhoea
- Urgency to urinate, frequent micturition
- Sweating, hot or cold flushes, flushing
- Muscle tension, trembling, shaking
- Feeling of instability and insecurity, weakness, weak knees
- Dizziness, light-headedness
- Numbness, paraesthesias (tingling sensations)
- Feeling faint, fear of collapsing
- Difficulty concentrating and remembering, thought block, ‘blackout’
- Fear of losing control, going mad, or dying
- Depersonalisation: sense of detachment from oneself or one’s own body; feeling of being disconnected from oneself
- Derealisation: sense of detachment from the current situation or environment; everything appears unreal, unfamiliar, ‘like a bad dream’

It is particularly noteworthy that the current manifestation of an anxiety state can show considerable inter- and intra-individual differences (Mason 1971). It is entirely possible that, instead of the full picture of a panic-like anxiety reaction, individual symptoms may occur largely in isolation. Moreover, an anxiety reaction in the same individual may manifest very differently in comparable situations at different times. The behaviour resulting from an anxiety or stress reaction cannot be generally predicted. The classical response patterns of 'fight' or 'flight', described by Cannon as early as 1915 (Cannon 2015), now occur in their original form in humans only rarely in social contexts. In cases of excessive, uncontrollable anxiety, these behavioural patterns are inhibited, resulting in an inability to act ('freeze'). Behavioural patterns attributable to the actual play-dead reflex (without preceding maximal sympathetic activation) are observed in humans during fainting episodes, such as those seen in blood, injection and injury phobias. A common behavioural consequence of anxiety reactions is avoidance. This is reasonable if the anxiety-provoking situation was genuinely dangerous, as it prevents the individual from exposing themselves to similar situations in the future. Conversely, avoidance behaviour leads to a fixation of the anxiety, as it precludes positive coping with such situations and thus prevents a reduction in the stress response to the triggering stimulus. From this, an important principle in dealing with anxiety can be derived: in the long term, the solution is not 'no stress', but rather a change in the subjective appraisal of the trigger. Put simply: to overcome a particular anxiety, one must face it. In this way, the original 'threat' can become a challenge that fosters personal growth.

> The typical symptoms of anxiety can be derived from the biological purpose of the stress response: preparing the organism for fight or flight. However, the specific manifestation can vary greatly between individuals and depending on the situation.

46.1.3 Controlled or Uncontrollable Stress: Internal Appraisal

The manner in which a stress reaction is processed plays a decisive role in determining its effects on actions, thoughts and emotions. To illustrate this, consider the two extreme forms of a stress response. In most cases, the stress response will lie somewhere along a continuum between these two extremes.

The Stress Response Is Largely Uncontrolled

The brain interprets an internal or external stimulus as an alarm situation. Immediately, preparation is made for flight or fight. Figuratively speaking, it is a matter of 'life or death'. Through the autonomic nervous system and stress hormones, every cell in the body is alerted to the state of emergency. If the individual feels helplessly at the mercy of the situation, as can occur during a severe panic attack, the process may, in extreme cases, lead to an inability to act and can progress to complete physical and mental-emotional exhaustion.

The Stress Response Is Controlled and Optimally Regulated

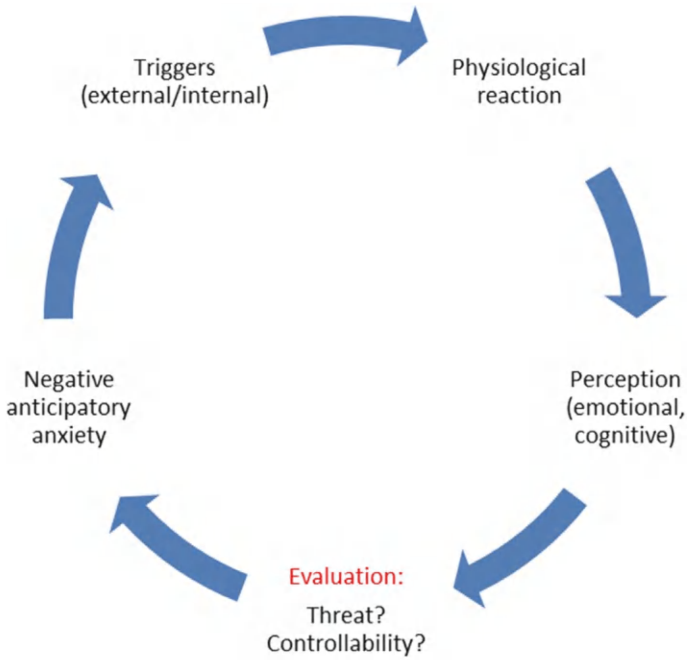
Often, control of the stress reaction begins even before the anticipated triggering situation (anticipatory stress response). For example, consider an imminent mountaineering activity. The state of arousal activates the body and many brain regions. Alertness, attention and concentration are heightened, thought processes are focused on the essentials, the muscles are slightly tensed and metabolic processes for energy provision are increased. This creates optimal conditions for mastering the upcoming challenge.

What, then, is the difference between a controlled and an uncontrolled stress reaction? Crucially, there are rapid and largely unconscious processes that internally appraise the triggering situation (Lazarus and Folkman 1984). By comparing the emotions that arise, previous experiences and memories, self-assessment and anticipation of possible consequences, a subjective assessment of the danger is arrived at. If, ultimately—initially in the form of a feeling—it is determined that the situation is manageable, the stress reaction can be controlled.

This appraisal process is, of course, not static, but rather a dynamic process that accompanies the stress reaction. Each appraisal, in turn, leads to modifications of physiological and psychological processes. This can be schematically illustrated by the anxiety cycle (◘ Fig. 46.1).

There are numerous studies on the effects of classical stress hormones (catecholamines and glucocorticoids) on various cerebral functions. It is worth noting that the concentration or dose exerts a decisive influence on subsequent processes. For example, cortisol initially has a beneficial effect on cognition, learning, and memory by promoting neuroplastic restructuring processes. In the long term, however, elevated doses of cortisol have the opposite effect (McEwen 2007).

Finally, the course of stress reactions is also dependent on the overall psychological, physical, and social baseline state of an individual. In addition to genetic predisposition, previous experiences, general physical fitness, or susceptibility to anxiety, factors such as current nutritional status (hunger), fluid and acid-base balance (thirst, stress at high altitude), oxygen saturation (hypoxia), current energy level (fatigue, exhaustion) and social security all play a crucial role.



◘ **Fig. 46.1** The anxiety cycle illustrates that an anxiety reaction constitutes a self-reinforcing process. Interruptions or exits from this dynamic are possible at any point

46.1.4 Anxiety and Stress as Illness

The boundaries between functional anxiety (‘eustress’), dysfunctional anxiety (‘distress’) and pathological anxiety are blurred, and this also applies to anxiety phenomena in alpine sports. A particular feature is that constructive management of anxiety can be regarded as a strong source of motivation for engaging in alpine sporting activities (Aufmuth 1988; Frankl 1993). It has already become clear in the preceding discussion how a positive approach to anxiety-inducing or stress-inducing situations can yield a subjective benefit. In this sense, anxiety leads to ‘pleasure’ (Balint 1959).

Conversely, it has also been discussed that ‘too much’ anxiety can have a negative impact on both psychological and physical performance. Alpinists who are generally characterised by increased anxiety susceptibility or who exhibit heightened anxiety reactions in certain situations, such as at exposed locations in the context of altitude intolerance, cannot, of course, be generally regarded as ‘ill’. Such individuals may even take fewer risks due to defensive behaviour. However, excessive anxiety susceptibility can also restrict or even prevent participation in certain alpine activities. Those affected may not be able to fully realise their performance potential. Excessive, dysfunctional anxieties greatly diminish the ‘pleasure gain’ of an alpine undertaking, and a sense of suffering may arise.

There are no precise figures on the number of mountaineers suffering from manifest anxiety disorders (Fagenholz et al. 2007). However, since anxiety disorders are very common in the general population (Bandelow and Michaelis 2015), an approximation can be made. On the one hand, individuals with increased anxiety *susceptibility* may even be particularly attracted to mountaineering activities as a form of counterphobic behaviour. On the other hand, people with manifest anxiety disorders typically exhibit avoidance behaviour, so that manifest anxiety disorders are likely to be less common among mountaineers than in the general population (Hüfner et al. 2022).

The following criteria are proposed as indicative of the presence of an anxiety disorder:

- Inappropriately intense fear or anxiety and/or corresponding physical symptoms;
- The symptoms cause significant distress;
- Excessive fears, worries, or concerns that restrict or prevent certain alpine activities (avoidance behaviour);
- Marked anxiety symptoms also outside or in anticipation of triggering situations (anticipatory anxiety).

> Anxiety disorders are frequently associated with other mental disorders (depressive disorders, obsessive-compulsive disorders, and substance use disorders).

An overview of the diagnostic classification of anxiety or fear-related disorders according to ICD-11, ► Chap. 6, is presented in the following systematics (WHO 2020; BfArM 2024):

- 6B00 Generalised anxiety disorder
- 6B01 Panic disorder
- 6B02 Agoraphobia
- 6B03 Specific phobia
- 6B04 Social anxiety disorder
- 6B05 Separation anxiety disorder
- 6C4x.71 Substance-induced anxiety disorders
- 6B23 Hypochondriasis

> Anxiety is a danger signal that can trigger a controlled or uncontrolled stress response. Ideally, anxiety can be transformed into pleasurable play; in the worst case, it can develop into a serious illness.

46.2 Vertigo and Fear of Heights

The relationship between vertigo and anxiety has been discussed in medicine for many years (Balaban and Jacob 2001). Even now, research offers differing approaches and interpretations. A distinction has been established between at least three phenomena: physiological balance disturbance during exposure to heights, visual height intolerance (vHI) and fear of heights (acrophobia) in the narrower sense (Huppert et al. 2020). The pleasurable experience of exposure to heights has been described as another possible response to height exposure (Salassa and Zapala 2009). Visual height intolerance and fear of heights occur in about one-third of the population at some point during their life (Brandt and Huppert 2014; Huppert et al. 2013). Affected individuals experience significant limitations in daily life, primarily due to avoidance behaviour. Comorbidities with mental disorders (affective disorders, anxiety disorders) and other vertigo syndromes are common (Huppert et al. 2020). As a clinical entity, fear of heights is of clinical relevance and is classified as a specific phobia according to DSM-5 and ICD-10 or ICD-11 (Falkai et al. 2018; WHO 2020; BfArM 2024). In non-medical contexts, however, the term ‘fear of heights’ does not always refer to a clinically relevant condition, but is often synonymous with visual height intolerance. To provide a clear distinction, physiological phenomena during height exposure and visual height intolerance are presented together, while fear of heights as a disorder requires separate consideration. The possibility of deriving pleasure from coping with stress or anxiety-provoking stimuli (Balint 1959) has already been addressed in the general discussion of these phenomena (▶ Sect. 46.1.4).

46.2.1 Physiological Phenomena during Height Exposure and Visual Height Intolerance (vHI)

Height-induced vertigo develops with a slight delay within seconds when fixed, high-contrast objects in the peripheral visual field are absent. For stabilisation of the body, in addition to the vestibular and proprioceptive systems, perception in the peripheral retina is required. When standing upright, these systems are more challenged than when sitting or lying down, which is why height-induced vertigo occurs predominantly in the standing position, especially on sloped or uneven surfaces (Salassa and Zapala 2009; Brandt et al. 1980).

Mild movements of the head and trunk such as swaying or oscillating are physiologically necessary to maintain balance. When height-induced vertigo occurs, these movements become more pronounced, so that destabilisation of the sense of balance can actually increase the risk of falling during alpine activities. Symptoms and measures against height-induced vertigo are listed in the following classification:

- Symptoms:
  - Intensification of physiological swaying or oscillating movements of the head and trunk,
  - Destabilisation of the balance system,
  - Sensation of vertigo,
  - ‘Pull’ downwards or the feeling of being drawn into the depths (transition to fear of heights).
- Exacerbation of symptoms with
  - Looking down into the depths,
  - Looking into the distance (e.g. sky, clouds, especially when they are moving),
  - Taking photographs, filming and looking through binoculars.

- Helpful countermeasures:
  - Avoid looking into the distance or at moving objects—focus on nearby objects,
  - Keep high-contrast objects in the peripheral field of vision,
  - Head upright, spine straight,
  - Choose a ground surface as even as possible,
  - If available, consciously use trekking poles for support,
  - Hold on to a fixed object or another (stationary) person,
  - If necessary, squat down, sit down or even lie down,
  - Regular training generally reduces height vertigo, depending on individual predisposition.

Height vertigo, or more precisely, the fear of depths, is an innate, instinctive function and has also been experimentally demonstrated in many animal species. It is not possible to specify an absolute height at which height vertigo occurs; however, the distance to the nearest visible object plays a decisive role.

With regular exposure, height vertigo usually diminishes or is efficiently suppressed by counter-regulation. Nevertheless, there is a certain individual predisposition, so that complete freedom from vertigo cannot be achieved by everyone (Domej et al. 2004).

46.2.2 Acrophobia

Acrophobia is an anxiety disorder and can be classified as a specific phobia in the WHO diagnostic manual (ICD-11, ► Chap. 6) (6B03).

Neurophysiological mechanisms underlying the development of anxiety, as well as the symptomatology of anxiety and stress in general, have already been discussed (◘ Fig. 46.1). Possible counterstrategies in the event of acrophobia, as well as medium- and long-term therapeutic options, are outlined below.

Helpful acute measures include

- Countermeasures for height vertigo.
- Providing closeness, safety, calm and composure.
- If possible, do not leave the triggering situation until the anxiety subsides.
- Simple breathing and relaxation exercises can be helpful (instructions can be found in specialised self-help literature or are freely available online).
- If necessary, turn back (if possible, a ‘controlled retreat’, not a ‘flight’).
- In extreme cases, pharmacological intervention may be considered, such as short-acting benzodiazepines (for related issues, see ► Sect. 46.3).
- Primary and secondary prevention: reduction of accompanying stress factors, such as physical overexertion, fatigue, hunger, thirst, heat or cold, social distress and emotional strain.

In cases of severe, recurrent anxiety reactions and impairment of quality of life (clinical acrophobia), the following approaches may be effective:

- Graduated self-directed exposure: repeated confrontation with triggering stimuli (exercises on suitable objects such as chairs, ladders, bridges, etc.); remain in the situation until the anxiety subsides. Initially, it may be helpful to perform the exercises in the presence of a trusted person. A simple, clearly written self-help guide is often useful. If there is no improvement, psychotherapeutic treatment should be sought.
- Therapist-guided exposure (in person or virtual): Behavioural interventions such as participant modelling, in which the therapist demonstrates certain exercises or performs them together with the client, have proven effective. Direct confrontation with the feared situation is generally highly efficient. Some studies

also indicate the effectiveness of Virtual Reality exposure for acrophobia (Bandelow et al. 2021; Emmelkamp et al. 2002).

▪ Long-Term Pharmacological Intervention

Sometimes, anxiety is triggered not only by the specific stimulus (height) but also by internal cues, such as the thought of the intended excursion. This can lead to a fear of fear itself (phobophobia). Furthermore, specific phobias such as acrophobia often co-occur with other anxiety disorders, such as agoraphobia or generalised anxiety disorder. In these cases, the question arises as to whether treatment with a modern antidepressant is indicated (▶ Sect. 46.3).

> Visual height intolerance (vHI) is a common phenomenon that can cause significant distress in affected individuals. Regular training (exposure) can usually have a favourable effect on symptoms. Acrophobia may trigger a pronounced stress response and must always be taken seriously. Specific psychotherapeutic or even pharmacological interventions may become necessary.

46.3 Pharmacological Interventions for Anxiety

The psychotropic drugs described below are generally used in the treatment of anxiety disorders and, when administered appropriately, are usually well tolerated and effective. However, particular caution is required when considering the use of these drug classes in the context of alpine sports activities. There is a lack of robust studies on possible adverse effects at moderate and high altitudes. In individual cases, pharmacological intervention may nevertheless be indicated. The recommendations are based on the German S3 guideline for the treatment of anxiety disorders (Bandelow et al. 2021).

46.3.1 Short-Term Interventions

Pharmacological treatment of anxiety states with benzodiazepines (BZDs) is generally not recommended due to their extensive side effects, including the risk of dependence. However, benzodiazepines do provide very good anxiolytic effects with a rapid onset of action. In well-justified exceptional cases, benzodiazepines may be used as a single dose or for the shortest possible duration, following careful consideration of the benefit-risk profile. Side effects and the potential for dependence must be strictly observed.

Possible adverse effects of benzodiazepines include

- Fatigue, drowsiness,
- Impaired attention and reaction time,
- Ataxia,
- Muscular weakness,
- Dizziness,
- Nausea,
- Headache,
- Anterograde amnesia (especially with rapidly acting BZDs),
- Paradoxical reactions (agitation, excitement, aggression, insomnia),
- Development of dependence (which may occur after only a few weeks of regular use).

Potential sedative and respiratory depressant effects are particularly limiting factors in the mountains and at high altitude. Even at low doses of BZDs, reduced attention, impaired reaction time, ataxia, apathy, and dizziness must be carefully considered during alpine activities (Kong 2021). The severity of possible side effects can vary greatly between individuals.

As in the treatment of anxiety disorders at sea level, alprazolam, lorazepam and oxazepam are the most suitable options, in individually adjusted, preferably low doses. It must be emphasised once again that the use of BZDs in the mountains should only be considered in extreme emergencies and under the supervision of physicians familiar with the respective substance. Uncritical, self-directed use should be strictly avoided.

The effects and accompanying reactions of benzodiazepines at high and moderate altitudes have not yet been systematically evaluated. However, there are some studies on the use of temazepam as a hypnotic in high-altitude mountaineering. The results are controversial, particularly due to marked nocturnal hypoventilation, and use cannot be recommended even for this indication (Kong 2021). Recent research findings suggest that even the use of BZD-like substances (zolpidem) is highly questionable, due to measurable cognitive and postural effects the following day (Bouzat et al. 2018).

46.3.2 Long-Term Interventions

For the pharmacological treatment of anxiety disorders, the selective serotonergic agents citalopram, escitalopram, paroxetine and sertraline, as well as the dual-acting (serotonergic and noradrenergic) venlafaxine, are recommended as first-line.

The onset of therapeutic effects after the initiation of regular intake usually takes several weeks. During the initial phase, side effects are more common and anxiety symptoms may temporarily worsen. Slow titration to optimise the dose, ideally including plasma level monitoring, may be necessary.

The use of these medications should be integrated into a comprehensive treatment plan that, in addition to psychoeducational elements, includes concurrent psychotherapy. Such treatment should therefore generally be supervised by a specialist (consultant psychiatrist and psychotherapist).

An interesting question is whether regular use of medications from this group may pose particular risks at altitude. However, the available data are insufficient to allow well-evidenced advice. Nevertheless, there are no obvious reasons why a well-established, effective, and well-tolerated medication should be discontinued before or during a mountaineering expedition. Conversely, abrupt discontinuation should be considered risky, as this may lead to withdrawal phenomena and a recurrence of anxiety symptoms.

> Psychotropic medications are not generally contraindicated in mountain sports but should only be prescribed by experienced physicians with particular attention to possible side effects. Established treatments with SSRIs and SNRIs that have proven effective and have not previously caused relevant adverse effects should not be discontinued indiscriminately prior to mountaineering activities.

46.4 Stress, Anxiety and Acute Mountain Sickness

In addition to the rate of ascent and the absolute altitude reached, an ‘individual predisposition’ is considered responsible for the likelihood of developing acute mountain sickness (AMS) (Roach et al. 2018). However, how this individual predisposition can be characterised remains unclear. Even the pathophysiological mechanisms leading to the onset of AMS appear to be diverse and individually variable (Berger et al. 2020).

Anxiety phenomena and stress factors have frequently been associated with the development of acute mountain sickness (Missoum et al. 1992; Waanders 2010; Boos et al. 2018; Gatterer et al. 2019; Hüfner et al. 2022). However, findings are inconsistent and sometimes contradictory (Niedermeier et al. 2017). Attempts to relate the partial pressure of oxygen to the development of AMS have also led to varying interpretations (Burtscher et al. 2019; Berger et al. 2020). However, oxygen deficiency represents one of the most potent stressors (Klein 1993), and hypoxia is generally regarded as an essential trigger for AMS.

Current research approaches are investigating hypoxia-induced changes at various systemic and molecular levels. Stress-relevant regulatory mechanisms, such as the hypothalamic-pituitary-adrenal axis, are affected by hypoxia, as are various neurotransmitter systems and inflammatory processes (Burtscher et al. 2022). Alterations in transcription factors, mitochondrial function, and redox systems also play a role (Mallet et al. 2023). There are apparent overlaps with the pathomechanisms of anxiety and stress, as well as affective and neurodegenerative disorders (Burtscher et al. 2022). To what extent these findings will lead to practical consequences for the prevention and treatment of AMS remains to be seen.

Hypoxia is undoubtedly a strong stressor. Stress and anxiety phenomena are associated with acute mountain sickness, but the precise mechanisms remain unclear. At present, no specific measures for the prevention and treatment of AMS can be derived from these findings, apart from the generally known behavioural strategies and pharmacological options.

Conclusion

Anxiety is a comprehensive phenomenon and can be described at the biological level using concepts of the neuroendocrine stress response. Whether this stress response has constructive or destructive effects for the individual depends in particular on the complex process of internal appraisal of anxiety-provoking stimuli.

Mountaineering provides an excellent medium for training in anxiety and stress management. For many mountaineers, this is often an unconscious but essential motivation for their alpine activities. However, excess anxiety can become a serious problem in the mountains and may require immediate treatment. This initially consists of behavioural interventions, and then, in exceptional cases, pharmacological interventions. In the longer term, in cases of clinically significant anxiety disorders, psychotherapeutic as well as pharmacological options should be used.

There is little reliable data on the epidemiology and significance of the (first) onset of clinically relevant anxiety disorders in the mountains; similarly, the use of pharmacological or psychotherapeutic interventions at high altitude has so far been insufficiently studied.

Acute mountain sickness results from a complex interplay of hypoxia and various individual factors, among which anxiety and stress play a role. Based on current knowledge, no specific prophylactic or therapeutic measures beyond the general recommendations (see ► Chap. 7) can (yet) be advised.

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Outlook

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47

New Technologies in Alpine and High-altitude Medicine

Michiel J. van Veelen and Hermann Brugger

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Introduction

Novel telemedical technologies can improve the exchange of information between patients and physicians in inaccessible and remote mountain regions, leading to earlier diagnosis. Drones can be used for locating missing persons and transporting medical equipment, thereby accelerating the initiation of targeted therapy.

The introduction of new technologies raises ethical and legal questions, such as the operation of dr3ones in shared airspace, international medical liability in telemedical consultations and quality assurance in applications such as point-of-care ultrasound (POCUS), for example, through certification and image storage.

47.1 Drones in Mountain Medicine

Unmanned aerial vehicles (UAVs), also known as drones, are small aircraft that can be piloted remotely from the ground or fly autonomously. In recent years, drones have become widespread due to technological advances and reduced costs. Numerous mountain rescue organisations have adopted the use of drones. Drones provide an aerial overview and can cover large search areas without endangering flight crews. They are also capable of transporting payloads and establishing communication, which can lead to more rapid treatment of patients in mountainous regions.

47.1.1 Search and Rescue

Drones equipped with high-resolution cameras, ultra-sensitive sensors and thermal imaging can scan large areas in a short time, thereby improving the efficiency of search operations for missing persons. The video footage captured by drones is transmitted in real time to a pilot or command centre, providing up-to-date information on the situation and current conditions in the field. This enables precise localisation of the person sought, reducing the time and effort required for ground-based search operations in difficult terrain. As a result, the treatment-free interval during search and rescue missions is shortened (van Veelen et al. 2023).

47.1.2 Mass Casualty Incidents (MCI) and Triage in the Mountains

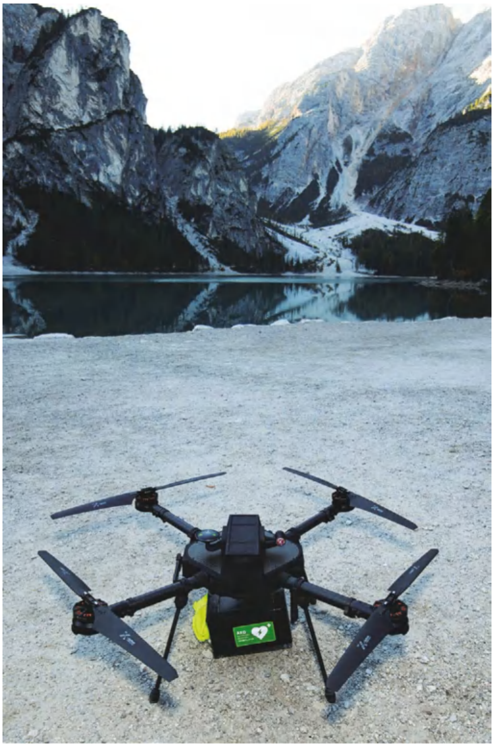
Drones can provide an overview of the overall situation during major incidents, which can assist with triage. Potential hazards can be identified in good time, improving the safety of rescuers, with low operating costs and without putting a flight crew at risk (Abrahamsen 2015). A significant example was the use of drones following the 2022 Marmolada glacier collapse in the Italian Dolomites, where the search for survivors could be continued after nightfall using aerial thermal imaging (Puetz 2022). Video-based photoplethysmography with measurement of heart and respiratory rates enables drones to support remote triage by confirming if victims show signs of life (Al-Naji et al. 2017).

47.1.3 Transport of Medical Equipment and Defibrillators

Medical kits containing first aid equipment have already been successfully airdropped by drones using parachutes in mountainous regions (van Veelen et al. 2023). In several studies and pilot projects, semi-automatic defibrillators (AEDs) have been delivered to the scene of a cardiac arrest in urban areas by autonomous drone flights. In 2022, for the first time, this resulted in a patient surviving a cardiac arrest due to timely defibrillation following drone delivery. The AED was operated by bystanders after delivery (Schierbeck et al. 2022). A simulation study in a highly frequented mountainous area (◘ Fig. 47.1) has now also demonstrated that the time to defibrillation is significantly shorter when an AED is delivered by drone to a bystander (2.2 min) compared to helicopter emergency services (HEMS)-performed defibrillation (18.2 min) or locally retrieved public accessible defibrillator on foot (12.4 min) (van Veelen et al. 2024).

47.1.4 Communication

Communication is often a challenge in mountainous terrain, especially when there is no cellular, satellite or radio connection. Drones can serve as radio relays or Wi-Fi hotspots, facilitating communication and coordination between rescue teams and control centres (McRae et al. 2021). In addition, they can establish communication with a remote physician to provide medical advice to companions or rescue personnel via radio or satellite (van Veelen et al. 2023).



◘ **Fig. 47.1** Drone with AED ready for take-off on the shore of Lake Braies, South Tyrol, Italy. (van Veelen et al. 2024; © Eurac Research, Andrea De Giovanni)

47.1.5 Challenges for the Future

The main obstacles to the deployment of drones are legal requirements, limitations in battery life and flight duration, dependence on weather conditions and the need for specialised training for drone pilots. However, ongoing improvements in drone technology, particularly in battery performance, durability and autonomous navigation, can partially overcome these challenges. The application of artificial intelligence will in future enable drones to autonomously navigate complex terrain, identify persons in distress and even perform advanced medical assessments and interventions remotely (Brugger et al. 2021). Specifically, deep reinforcement learning (DRL) directing drone search patterns across complex alpine terrain have potential to reduce search times (Bialas et al. 2024). Furthermore, the combination of telemedicine and drone deployment can enable medical professionals to provide remote assistance.

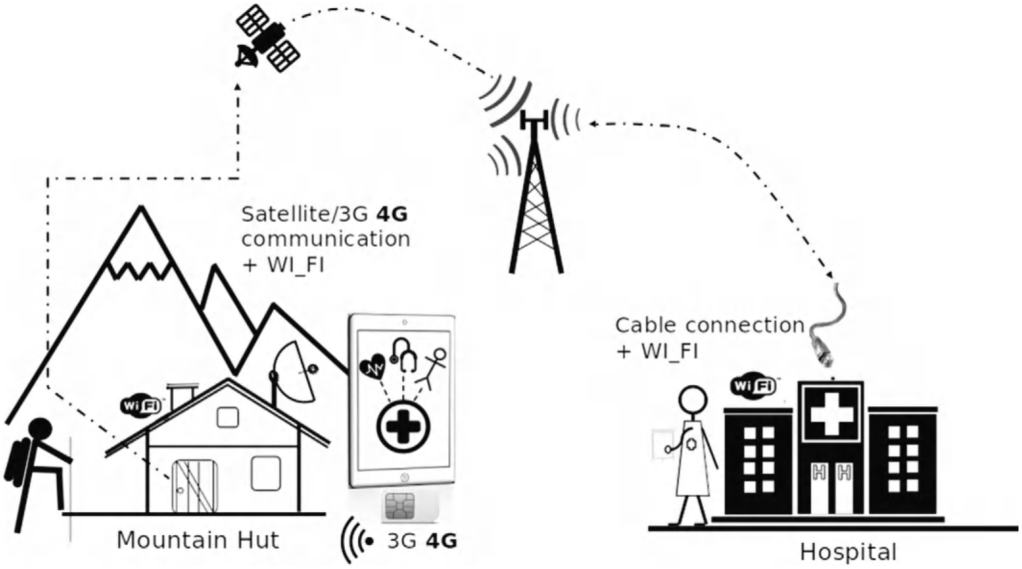
Ad hoc flight authorisations in shared airspace remain a challenge. Legal frameworks restrict the granting of flight permissions, especially for autonomous flights. This currently limits the use of drones in organised rescue services and, in particular, the simultaneous operation of drones and rescue helicopters. Regulations for airspace monitoring and shared airspace use are under development. Using a low-altitude-flight elevation model (LAFEM) where drones fly below shared airspace altitude could be an alternative. (Fajardo-Figueroa et al. 2024).

47.2 Telemedicine in Mountain Medicine

Telemedicine is the provision of healthcare at a distance. The aim of telemedicine is the diagnosis, monitoring and treatment of patients using telecommunication technologies. In mountain regions, it can be difficult for patients to reach a doctor or clinic. During mountain tours and expeditions, it cannot be assumed that a physician will always be available. Finally, even in the European Alps, terrestrial rescue teams consisting of paramedics and mountain rescuers can benefit from access to telemedicine when a mountain rescue doctor is not available. Body-worn sensors and portable devices enable (continuous) recording and transmission of vital parameters such as heart rate, blood pressure, oxygen saturation, temperature and ECG. The data can be transmitted to remote physicians via mobile or satellite connection. As data transmission rates in satellite communication networks have increased, live images and video transmissions are now possible worldwide.

In the Aosta Valley in the Italian Alps, telemedical support for mountain huts by hospital physicians, including the transmission of vital data combined with video, has already been successfully implemented (Martinelli et al. 2022; ◘ Fig. 47.2). Using the same platform, a Sherpa with severe respiratory insufficiency in the Khumbu region of Nepal was treated, demonstrating that distance is not a limiting factor for telemedical care and can also be successfully applied in expedition medicine. The remote performance of a thoracic ultrasound examination has been documented at an altitude of 6400 m. In this case, a satellite connection was established from the Advanced Base Camp on Mount Everest to an expert, who remotely guided and assessed the thoracic ultrasound (Otto et al. 2009).

During mountain sports, endurance events and altitude training, monitoring can be carried out using smart sensors integrated into clothing or chest straps (Pegoraro et al. 2023). These provide important information for medical supervision and for the prevention of overexertion, without impairing ath-



◘ **Fig. 47.2** The connection scheme for wireless and remotely controlled telemedical consultation in the Aosta Valley, Italy. (From Martinelli et al. 2022, with kind permission) letic performance. For example, Everest climbers were monitored remotely and in real time by continuous ECG recording and GPS tracking via satellite transmission throughout the entire ascent and descent, as well as during sleep (Kao et al. 2013; Di Rienzo et al. 2010). Data from portable devices can also be recorded and stored on smartphones.

Special sensors have been developed for the diagnosis of hypothermia. Skin temperature can be monitored by skin sensors, and core temperature by the oral ingestion of a capsule that remains in the body for a limited time and transmits temperature data telemetrically. Novel, non-invasive ear sensors with thermal insulation have been developed to measure tympanic temperature, which shows a strong correlation with core temperature. At the same time, heart rate and oxygen saturation can also be measured (Masè et al. 2024). These recordings are crucial for the treatment and triage of snow-buried persons and patients with accidental hypothermia and can be transmitted wirelessly to a monitor or smartphone. The telemedical transmission of images of frostbite is available around the clock in England and in the European Alps, enabling experts to advise both patients and treating physicians remotely. A similar 24/7 hotline, as provided by the Divers Alert Network (DAN), would also be desirable for the management of altitude illness in trekkers and mountaineers.

However, there are still legal concerns regarding telemedical remote care. For example, in most legal systems, it is not permitted to prescribe medication to patients without prior physician-patient relationship. Another issue is the legal protection of the person providing care to patients following telemedical consultation, such as a mountain guide or mountain rescuer, if they are not medical professionals. Numerous legal questions regarding the competence and responsibility of doctors working across borders, but not registered with the professional bodies of the country where the treatment takes place, and liability in the event of a legal claim, remain unclear. As a guideline, it is recommended to consider the forensic principles listed below, which were published on the subject of telemedicine in expedition medicine by Szawarski and Hillebrandt (2017).

Forensic Principles for Telemedicine in Expeditions (Szawarski and Hillebrandt 2017)

- The risks associated with the expedition should be known to all parties.
- The scope of telemedical activity should be defined in advance.
- Local or national legal regulations on telemedicine should be observed.
- For commercial expeditions, a medical triage for risk assessment should be carried out prior to the expedition.
- For commercial expeditions, the organiser bears responsibility; therefore, consent for the transfer of participants' medical information to the organiser should be obtained.
- Doctors should act only within the limits of their competence.
- Consent should also be obtained if others are involved in the exchange of information.
- Limitations arising from the lack of direct contact should be communicated transparently.
- Others acting on behalf of a doctor (e.g. expedition leaders) should do so in the best interests of the patient and with the patient's consent.
- Clinical records should be kept and stored according to personal data security standards.
- Communication equipment should be properly maintained.

(continued)

- The practice of telemedicine should be subject to evaluation and subject to continuous professional development.

47.3 Point-of-Care Ultrasound in Mountain Medicine

Point-of-care ultrasound (POCUS) is of undeniable value in the hospital setting, particularly in the emergency department and intensive care unit for the rapid assessment of acute and critically ill patients with trauma, dyspnoea or shock, as well as for bedside monitoring of vital parameters by physicians. Recent technological advances have resulted in portable, cost-effective devices becoming available to medically trained emergency personnel. This has enhanced the ability to assess patients quickly and reliably also in the pre-hospital setting.

Ground-based emergency physicians, HEMS physicians and emergency medical personnel frequently care for critically ill and injured patients in difficult terrain, where resources are limited and time-critical emergency interventions may be required before transport and arrival at the resuscitation bay. POCUS provides real-time imaging, delivering information for rapid diagnosis and assessment of urgency, thereby enabling the optimal choice of destination facility for transport and recognising the need for an emergency intervention. For example, a ventilated trauma patient with a pneumothorax may rapidly develop haemodynamic instability or even suffer cardiac arrest through tension pneumothorax during transport if not decompressed beforehand.

On a high-altitude expedition, doctors may encounter patients with respiratory distress. Differentiating between various causes such as high-altitude pulmonary oedema (HAPE), pneumonia or other conditions can be supported by targeted POCUS examinations (Yang et al. 2018). This leads to a reliable differential diagnosis, enabling targeted treatment or evacuation. The diagnosis of acute mountain sickness (AMS) and high-altitude cerebral oedema (HACE) may be supported by ultrasound examination of the optic nerve (Lochner et al. 2015). Ultrasound images or even live examinations can be remotely monitored by physicians, bringing POCUS into the realm of telemedicine. This section describes general protocols and applications for POCUS in pre-hospital emergency medicine and expedition medicine. As with any new clinical application, appropriate training, device approval and data security in image storage are important considerations that must be addressed.

47.3.1 POCUS in Pre-hospital Emergency Medicine

In hazardous situations, technical rescues and difficult terrain, extensive examinations should not delay patient transport. For decision-making, it is therefore advisable to use standardised protocols for the examination process and clear guidelines for interpretation of findings (Bøtker et al. 2018). POCUS is gaining ground in prehospital emergency medicine, with an increasing number of reports of its use. A recent prospective study at a HEMS operator found that POCUS examinations were performed in more than one-third of patients and had therapeutic consequences in almost half of these cases (Vianen et al. 2023).

47.3.1.1 E-FAST (Extended Focused Assessment with Sonography for Trauma)

E-FAST is a protocol developed for the rapid assessment of trauma patients (van der Weide et al. 2019). It involves examining

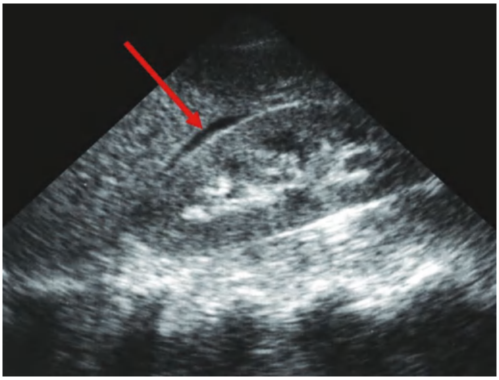


Fig. 47.3 Ultrasound examination of the right abdominal side shows free fluid in Morison's pouch (hepatorenal recess) between the liver and right kidney (*red arrow*) as part of the E-FAST examination. (© M. J. van Veelen)

various body regions for signs of internal injury. The abdomen is assessed for free fluid, which may indicate internal bleeding (Fig. 47.3). Cardiac assessment involves checking the pericardial space for effusion, while thoracic examination can identify a pneumothorax. This protocol accelerates and improves trauma assessment, facilitating early intervention and optimal choice of destination facility.

47.3.1.2 RUSH (Rapid Ultrasound in Shock)

RUSH is tailored to patients in shock (Perera et al. 2010). It comprises a standardised examination of the heart, lungs, and inferior vena cava to determine the type of shock (hypovolaemic, cardiogenic, distributive or obstructive). The RUSH examination enables immediate identification of hypovolaemia, pneumothorax or cardiac tamponade, enabling prompt intervention. As well as a comprehensive protocol, training and experience are crucial for successful implementation, especially under adverse prehospital conditions.

47.3.1.3 BLUE (Bedside Lung Ultrasound in Emergency)

The BLUE protocol was developed to identify the causes of dyspnoea such as pulmonary oedema, pleural effusion, pneumonia, pulmonary embolism or pneumothorax (Lichtenstein 2014). Three standardised lung views on both sides of the chest can reveal the presence of horizontal or vertical artefacts (A- or B-lines), consolidations, and lung sliding. The algorithm assists in making a diagnosis more or less likely based on the combined findings in these views.

47.3.2 POCUS in Expedition Medicine

In high-altitude medicine, POCUS is a valuable diagnostic tool for the expedition physician. In addition to supporting the assessment of critically ill patients, it can facilitate the diagnosis of musculoskeletal injuries such as fractures and dislocations, abdominal conditions such as appendicitis or hernia, skin problems such as abscesses, urological issues such as retention, testicular torsion or even the diagnosis of pregnancy (Canepa and Harris 2019). Confirming or ruling out these diagnoses can help guide decisions on whether to evacuate the patient early or to manage the condition on site. Beyond these internal and traumatic conditions, expedition members at extreme altitude are at risk of acute altitude illnesses such as HAPE and HACE, which must be recognised at an early stage before they become life-threatening. These conditions can be difficult to distinguish from other causes of shortness of breath or altered behaviour (van Veelen et al. 2025). POCUS, particularly through the detection of B-lines and measurement of the optic nerve sheath diameter (ONSD), could play a role in ruling out or diagnosing these conditions (Luks et al. 2024; Wipplinger et al. 2021).

47.3.2.1 High-altitude Pulmonary Oedema (HAPE)

HAPE is characterised by fluid accumulation in the lungs, leading to impaired oxygen exchange and shortness of breath. B-lines are vertical comet-tail artefacts observed during lung ultrasound, indicating interstitial oedema. In the context of dyspnoea at high altitude, the identification of B-lines on portable ultrasound is a sensitive but non-specific diagnostic tool for detecting HAPE (Luks et al. 2024). A strong negative correlation between arterial oxygen saturation and the number of B-lines has been demonstrated at 5160 m (Lim et al. 2019).

47.3.2.2 Acute Mountain Sickness (AMS) and High-altitude Cerebral Oedema (HACE)

The pathogenesis of AMS is not yet fully understood, but is likely related to the onset of cerebral oedema, altered cerebral blood flow, and changes in the blood-brain barrier. However, there is no clear correlation between changes in ONSD and the occurrence of acute mountain sickness, as the various studies are inconsistent and inconclusive, limiting the diagnostic accuracy of ONSD for AMS (Lochner et al. 2015). HACE is considered a severe form of AMS. The symptoms are associated with increased intracranial pressure, which, together with encephalopathy, leads to neurological symptoms such as ataxia and altered behaviour, which, if untreated, can progress to coma and death. The rise in intracranial pressure correlates with an increased ONSD (Kimberly et al. 2008). An increase in ONSD over the course of several ultrasound measurements may indicate the development of HACE, although this has yet to be confirmed.

> **Conclusion**
>
> Drones, telemedicine and point-of-care ultrasound (POCUS) are new technologies that can improve healthcare delivery in mountain regions. Drones are revolutionising the search and rescue of accident victims, delivering medical supplies and out-of-hospital cardiac arrest care and enhancing communication in challenging terrains. Telemedicine utilises portable devices for remote monitoring of vital parameters and enables live consultations. POCUS expands the possibilities in emergency medicine and on expeditions, accelerating diagnostics and thereby improving medical care.

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Supplementary Information

The Standard Reference Work on Mountain and High-Altitude Medicine – 624

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The Standard Reference Work on Mountain and High-Altitude Medicine

Renowned mountain and high-altitude medicine experts from the German-speaking area and beyond provide a comprehensive overview of mountain sports, emergency medicine in the mountains, and high-altitude medicine in this specialised book. The book covers all content for the 'International Diploma in Mountain Medicine' (DIMM) of the World Federation of Alpine Associations (UIAA), the International Commission for Alpine Rescue (ICAR), and the International Society for Mountain Medicine (ISMM) and is recommended by the Austrian Society for Alpine, High Altitude Medicine (ÖGAHM), and the German Society for Mountain and Expedition Medicine (BExMed).

The book is a translation of the German third edition “Alpin- und Höhenmedizin”, which has been extensively updated. New chapters have been added on pulse oximetry at high altitude, neurological and psychiatric emergencies in the mountains, multiple trauma in the mountains, suspension syndrome, and new search and rescue technology in the mountains. Numerous other chapters have been updated and thoroughly revised.

The book is aimed at mountain physicians, sports medicine specialists, travel medicine physicians, medical personnel and physicians involved in emergency medicine and mountain rescue, and all physicians and professional groups interested in mountain and high-altitude medicine.

Contents:

- History of Mountain Medicine
- High-Altitude Medicine
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